Aggregate Model and Analysis of the Energy Dynamics in the Kingdom of Saudi Arabia

By

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System Design and Management Program

May 11, 2012

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Professor Olivier de Weck
Thesis Supervisor
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Patrick C. Hale
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Dedication

This thesis is dedicated to my parents and my brothers and sisters. My older sister Farida deserves special mention, for playing a vital role in my academic development in my early school years. I am also grateful to my lovely wife Sarah for her support of my work, and to my son Faisal whose future inspired me to choose this topic.

Acknowledgments

This research would have not been possible without the guidance and help of several individuals. I owe Dr. Olivier de Weck my utmost gratitude for his sincere guidance, encouragement, and support from the first day, and every step of this research. My fellow researchers at the Center for Complex Engineering Systems (CCES) here at MIT and the CCES team in King Abdulaziz City for Science and Technology in Saudi Arabia provided guidance, feedback, and help in the data collection process.

The time I have spent with my colleagues at the System Design and Management program in the classroom and on projects has proven to be one of the most rewarding of aspects of my work here. Their diverse backgrounds and expertise have contributed immensely to my learning experience at MIT. My other colleagues at the MIT Sloan School of Management have added immensely to my academic and personal growth.
Abstract

The Kingdom of Saudi Arabia is facing a crisis in the near future centered on increasing energy consumption. Today, the kingdom consumes approximately 1/3 of its oil production. If no action is taken and the kingdom continues business as usual, by 2026 it will consume 50% of its production, and by 2047 its entire production. A large percentage of oil produced in the kingdom is used for electrical generation and to fulfill increasing industrial, transportation, and water demand. In 2010 the kingdom consumed 212,262.6 GWh—9.7% more electricity than in the previous year. This thesis analyzes how the current situation has developed, then lays out the important elements of Saudi energy dynamics on a national scale. The following chapters demonstrate the application of causal loop analysis to the Saudi situation through a system dynamics model. Technical, financial, and socio-economic challenges in energy management were used to derive key dynamic variables included in the model which shows how increasing GDP and population drive local electrical demand. Energy policy scenarios involving increased use of natural gas and/or diversification into solar electrical generation were simulated by the model. The model showed that the result would be increased oil exports, which in return yielded a higher GDP and more investments in economic and industrial growth. The output of the model showed that diversification would defer the crisis for only a few years if current consumption trends continue. A hybrid scenario that couples diversification with an aggressive energy efficiency policy to stimulate reduced consumption demonstrated electrical consumption levels below 400,000 GWh, sustainable over the next 35 years. In all other scenarios electrical consumption increased rapidly beyond 600,000 GWh over the same period. The thesis concludes with some key findings and recommendations for the future development of sustainable energy policies in the kingdom and the region.
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Introduction

This study uses systems dynamics to model potential directions for managing rapidly increasing electricity consumption in the Kingdom of Saudi Arabia (KSA). Saudi Arabia has felt the impacts of a rapidly growing population, and an aggressive industrial and urban expansion. The critical links between energy production, population growth, industrial expansion, and electricity consumption are discussed below. In this, the kingdom parallels a similar evolution of other rapidly evolving nations worldwide.

Energy abundance in the form of petroleum reserves, and global oil prices have created cycles of oil booms in the kingdom, to which the Saudi government has responded with massive spending on infrastructure, industrial expansion, education, and many other areas. Though low oil cycles have been met with conservative spending, the cumulative effect of oil booms has contributed to the development of the nation over the past 80 years.

That development has been contributed to increased energy demand. The kingdom today is faced with a domestic energy crisis in a period of relatively high global oil prices (on the order of $100 per barrel). Government officials are challenged to make smart and calculated decisions that would guarantee the energy security today and the wealth and sustainability of the nation tomorrow. This study focuses on electrical consumption as a main driver of energy consumption.
However, improved electricity consumption and management in Saudi Arabia require approaches that reflect the kingdom’s unique combination of industrial, cultural, and geographical characteristics. This study develops and combines several system dynamics models, applying different ways to understand the causal loop effects of electricity use in Saudi Arabia. Included are analyses of the potential impact of alternative energy options, particularly solar energy. The study concludes with recommendations for government policy tailored to Saudi Arabia’s people and energy requirements that will help reshape the current energy system and set it on a more sustainable trajectory.

Organization of the Thesis

In this thesis, Saudi Arabia’s energy challenge is highlighted in chapter 1, and the current energy facts are laid out to explain the causes of the energy crisis in the kingdom. The effect of population growth and industrial activity on water and electrical consumption is then discussed. The chapter concludes with a list of potential remedies to the energy problem. The effectiveness of these remedial actions will then be quantified and tested in subsequent chapters.

Chapter 2 focuses on electrical consumption in the kingdom and current demand and consumption per capita, as well as consumption by sector and operational area. The chapter also lists the types of fuels used for electrical generation, their efficiencies, and the price of electricity as a major factor in the energy challenge.
Chapter 3 discusses the value of system dynamics as a non-linear method to analyze the current aggregate situation in the kingdom as well as the possible outcomes of government energy policies. This chapter includes a step-by-step explanation of building a system dynamics model. It also lays out the complexities of mapping variables and representing the current energy situation as a validated system dynamics model.

Chapter 4 presents the potential value of energy conservation and efficiency. A system dynamics model suggests that savings could be realized through technical efficiency in air conditioning units and more conservative consumer behavior. The model assumes that government subsidies that promote efficiency and investment in awareness are critical to achieving energy savings in the long run.

Chapter 5 discusses the possibilities of utilizing alternative energy sources for electrical generation and presents another system dynamics model that represents the potential growth of solar energy use in the kingdom. The chapter includes data about the type of solar technology that is most suitable for the kingdom based on geographical data, atmospheric conditions and solar irradiation. The solar discussion concludes with other potential uses of solar technologies in the kingdom.
Chapter 6 shows the aggregation of all the system dynamics models developed in Chapters 3 and 5 into an integrated model, and presents four different scenarios and their outcomes. The objective of the analysis is to identify the most effective approach to the energy problem based on the aggregate system dynamics model as a decision support tool. A set of model output variables are monitored and analyzed in each simulation scenario.

Chapter 7 reviews and discusses the conclusions of the study. Based on the system dynamics model presented and analysis of the data, a set of energy policy recommendations is presented. The chapter also lists future areas of research that might be studied under the umbrella of energy diversification in Saudi Arabia.
Chapter 1: The Case for Energy Diversification in Saudi Arabia

The Energy Challenge

The Kingdom of Saudi Arabia (KSA) relies heavily on the burning of fossil fuels but has the potential to develop sustainable energy technologies with world-wide applicability. Today, the Kingdom is delving into nuclear and renewable energy sources in an effort to reduce its reliance on hydrocarbons. At present (2010) approximately 877,000 barrels of oil are used per day for electricity generation, corresponding to about 320 million barrels per year (Singh 2010). This represents roughly 10% of Saudi oil production. All this is occurring in parallel to rapid industrial and residential growth. At the current rate and by continuing business as usual, by 2030 this acceleration will increase internal consumption and reliance on fossil fuels for electrical generation to approximately three times the amount that is consumed today.

![Saudi Arabia's Domestic Oil Consumption (BOE)](Jadwa 2011)

**Figure 1.1 – Saudi Arabia’s Domestic Oil Consumption (BOE)**

In 2009, the kingdom’s per capita primary energy consumption was at 6.8 tons of oil equivalent (toe), almost four times the world average that year (1.8 toe). According to
the KSA Energy Efficiency Report, energy consumption has grown at a rate of 5.8% per year since 1990, tripling between 1990 and 2009 (Enerdata). This rapid growth in primary energy consumption will surely continue if no corrective measures are taken. Action must be taken to control energy consumption and protect natural energy resources while sustaining economic growth and mitigating environmental impact.

Saudi Arabia’s electrical energy challenge is aggravated by a combination of technical, financial, and socio-economic challenges:

<table>
<thead>
<tr>
<th>Technical</th>
<th>Financial</th>
<th>Socio-economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Seasonal variability in electricity consumption and load distribution.</td>
<td>• Need for large capital investments to address current and future energy issues</td>
<td>• Lack of public utility staff awareness</td>
</tr>
<tr>
<td>Cooling load peaks during summer.</td>
<td>• Inclusion of environmental cost in any power project</td>
<td>• Wasteful energy consumption behavior of individuals and businesses</td>
</tr>
<tr>
<td>• Low generation capacity reserve margins</td>
<td>• Increase in loans to the Saudi Electrical Company (SEC)</td>
<td>• Rapidly increasing demand driven by social and economic development</td>
</tr>
<tr>
<td>• Lack of standards, legislation, and building codes to promote energy conservation</td>
<td>• Continuous use of subsidized energy costs to local consumers</td>
<td>• Population growth</td>
</tr>
<tr>
<td>• Lack of accurate centralized information from refineries and power generation plants</td>
<td></td>
<td>• Incompatible tariff structure and social/ economic welfare objectives</td>
</tr>
</tbody>
</table>

Table 1.1 – Challenges to Effective Management of Energy Consumption in KSA (Al-Ajlan 2006)

To address the complexities and challenges of industrial and economic expansion as well as population growth, decision makers and stakeholders require a model that enables
them to better understand current energy flows in the kingdom. Because regional and sectoral demand for energy varies, managers need an improved understanding of more specific supply and demand dynamics. A linear model that simply projects forward past growth trends is insufficient because it does not account for the coupled nature of the underlying dynamics of the energy system and the emergent behaviors (both helpful and detrimental) caused by various policy actions.

While many technical modeling methods exist, this study contends that simulating a combination of models is the only way to understand the problem in detail sufficient to indicate appropriate measures to resolve it.

Forecasts indicate that primary energy consumption will sharply increase in the next 30 years. The government is aware that the kingdom’s rapid increases in water and electricity demand are driven by a combination of high population growth, urbanization, lack of efficiency, and economic development. In response, the government continues to invest heavily in expanding refining capacity and boosting natural gas production. At the same time it continues to support the petrochemical industry as well as the non-oil-intensive sectors to boost the economy more broadly (QNB Capital). Capacity expansion is an obvious action to be taken faced with increasing demand. One of the objectives of this research, however, is to investigate other actions that could be taken, either alone, or in conjunction with capacity expansion that could lead to a better future state.
Population Growth

It has been argued that population growth is the main driver of energy consumption worldwide. In his article, Paul Chefurka (2007) argues that overpopulation is the root of all converging crises in today's world. He claims that the environment is unable to keep up with what an exploding population needs across all sectors including food, energy, waste disposal, air, fresh water, etc. While a detailed analysis of world population and energy growth is not essential to the argument presented here, the relationship is discussed below to set the stage for the study as a whole and to underscore the urgency of the problem.

Chefurka introduced the term “Carrying Capacity” which is basically defined as the population level that can be supported sustainably using available resources. Therefore, it can be inferred that an increase in population is an advance toward the limits of planetary carrying capacity. However, carrying capacity can be expanded in some dimensions as we discover more resources (oil, metals, uninhabited land, etc.) or introduce new technologies to exploit them more efficiently. One major resource that has contributed to the exploding global population is available energy, more specifically oil energy as well as advances in other areas such as agriculture and health care.

Figure 1.2 below, shows the increase in human population over the last 2000 years. It also shows use of oil more and more intensively as a source of energy beginning around 1900. Though many other factors contributed to rapid population growth in the last 100
years, we can infer that energy abundance has played a major role in the expansion and
development of other industries that eventually led to such growth.

Figure 1.2 – World Population and Oil Production (2000 Years) (Chefurka 2007)

Figure 1.3 shows a strong correlation between oil-based energy production and global
population growth during the twentieth century. Oil has enabled us to grow many other
industries resulting in an increase in global carrying capacity through urbanization, food
production, and discovery of more finite resources.
On a national scale, Saudi Arabia has followed that global trend; population has grown in parallel to the increase in oil production. The total population of the kingdom today, approximately 27 million people, coupled with increasing per capita energy consumption, is a major driver of energy consumption in Saudi Arabia. If these trends continue, more energy will be required to increase the “carrying capacity” for Saudi Arabia. The diagram below shows the kingdom’s population over the past 50 years, a sharp increase for the period after 1980, and even a slightly sharper increase after 2000.
Though the current population is around 27 million people, Saudi Arabian nationals represent only 66% of the population (18 million). With the rapid growth of many industries, the number of expatriates working in the kingdom continues to contribute to population growth. In 2010 Saudi Arabia ranked fourth in immigration among all countries. As part of a program of “Saudization”, KSA now requires local companies to employ a percentage of Saudi nationals. Despite such laws, the number of immigrants is likely to stay high due to rapid economic growth in non-oil sectors.
Other elements are contributing to the increased population of Saudi Arabia. For example, life expectancy is currently at 73.3 years, significantly higher than the 44.5 years it was in 1960. Also, higher fertility rates and a sharp drop in infant mortality rate have all contributed to the population increase in the kingdom (Chefurka 2007). Based on the “carrying capacity” argument and experience from developed nations, one can anticipate that population growth in Saudi Arabia will eventually slow and level off in the next 50 years. Other factors contributing to the decrease in population growth are increased economic development, rising GDP, higher levels of education, as well as the involvement of women in the workforce. In addition, the cost of energy and other resources in the kingdom will together challenge the high growth rates of the last 40 years.

Changes in women’s lives have combined to reduce the fertility rate in the kingdom. Women are getting married at a more advanced age than they have in the past 30 years. While no specific data is available, the author has observed that many married women are delaying pregnancy. As more women are educated and obtain higher degrees, they want to work; to do so, they will reduce the number of children they eventually have as well as delay the birth of the first child. The rising divorce rate among young couples may also contribute to lower fertility rates.
**Water Consumption**

The water situation in Saudi Arabia is one of most critical factors in energy consumption. The kingdom’s water consumption per capita is the third highest in the world--350 liters/capita/day (SAMA 2011). This level of consumption far exceeds the capacity of natural aquifers. Demand for urban water consumption is increasingly met through the energy-intensive process of desalination. Most of the freshwater withdrawals today are from fossil aquifers and about 85% of water consumption occurs in agriculture.

Water consumption in the past 30 years in agriculture was driven largely by the “wheat subsidization program”. In the past few years the kingdom has scaled back this program. Curtailment of the program led to an overall reduction of 4.8% of total water consumption. Meanwhile, water consumption in the industrial sector rose by 2%. Industrial expansion and its water requirements are likely to continue to grow in the next 30 years.

Despite the aggressive reduction of the “wheat subsidization program” and the resulting water savings through food imports, the kingdom realizes the upcoming demands, and continues to invest in water desalination. The capacity of the Saline Water Conversion Corporation (SWCC) is currently at 3.2 million cubic meters/day. Another 1.7 million cubic meters/day are produced by privately owned plants. QNB Capital reports that, “there are plans to double the capacity by building ten new desalination plants in 2010-2014 of which around half will be private” (QNB Capital 2007).
According to SWCC, the two methods currently used for water desalination in the kingdom are multi-stage flash distillation and reverse osmosis. The majority of the plants run the multi-stage flash process. Because this method requires a large amount of power to evaporate the water, desalinization is a major consumer of oil and gas. However, some amount of electricity is then recovered through co-generation via steam turbines.

![Map of Saudi Arabia showing saline water conversion plants and served cities](image)

**Figure 1.6 – National Saline Water Conversion Plants and Served Cities in Saudi Arabia**

The table below shows the current capacity of all major water desalination plants in the kingdom:

---

1 Map does not include water desalination plants that are owned by the private sector
<table>
<thead>
<tr>
<th>Company Name</th>
<th>Number of Plants</th>
<th>Electrical Generation Capacity (MWh)</th>
<th>Water Desalination Capacity (cubic meter / day)</th>
<th>Steam Production (ton/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Saline Water Conversion Co.</td>
<td>15</td>
<td>5,120</td>
<td>3,246,950</td>
<td>25,613</td>
</tr>
<tr>
<td>Jubail Water and Electricity Co.</td>
<td>1</td>
<td>2,942</td>
<td>805,464</td>
<td>5,170</td>
</tr>
<tr>
<td>Shauibah Water and Elec. Co.</td>
<td>1</td>
<td>1,191</td>
<td>888,000</td>
<td>-</td>
</tr>
<tr>
<td>Tuhamah Power Co.</td>
<td>4</td>
<td>1,083</td>
<td>-</td>
<td>4,405</td>
</tr>
<tr>
<td>Marafiq Co. (Yanbu)</td>
<td>1</td>
<td>1,038</td>
<td>95,760</td>
<td>-</td>
</tr>
<tr>
<td>Alshaqeeq Water and Electricity Co.</td>
<td>1</td>
<td>1,020</td>
<td>216,000</td>
<td>-</td>
</tr>
<tr>
<td>Rabigh Arabia Water and Electricity Co.</td>
<td>1</td>
<td>481</td>
<td>172,042</td>
<td>3,819</td>
</tr>
<tr>
<td>Jubail Electricity Co.</td>
<td>1</td>
<td>250</td>
<td>-</td>
<td>510</td>
</tr>
<tr>
<td>Shuaiba Expansion Project</td>
<td>1</td>
<td>-</td>
<td>150,000</td>
<td>-</td>
</tr>
<tr>
<td>Bawarij International Co.</td>
<td>2</td>
<td>-</td>
<td>52,000</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>13,125</td>
<td>5,626,216</td>
<td>39,517</td>
</tr>
</tbody>
</table>

Table 1.2 – Water Desalination Plants in Saudi Arabia (status 2010)

The ministry of water and electricity (MOWE) is taking strategic steps through the National Water Corporation to raise the performance and efficiency level of water and sewage facilities through:

1. Reforming procedures on a national level to improve demand management;
2. Internal changes and restructuring procedures to establish advanced centers for client services and organizational structures;
3. Raising awareness of water consumption issues and encouraging wise use; and
4. Attracting investment, domestically and internationally. (SAMA 2011)

The important element of awareness and rationalization of consumption will be discussed in later chapters.
Water consumption in the kingdom is the second highest among the major oil-exporting countries in the region in terms of the water used as a percentage of renewable resources available. Figure 1.7 shows the severity of the water problem in the region in terms of consumption per capita. The demand gap will continue to increase if consumption levels remain the same while the population continues to grow.

Figure 1.7 – Per Capita Water Consumption in Middle Eastern Oil Producing Countries

**Remedies to the Energy Problem**

To address these challenges, government officials in Saudi Arabia established the Saudi Energy Efficiency Center (SEEC) on October 31, 2010. The center is supervised by a committee of stakeholders that include the ministry of water and electricity, Saudi Aramco, the Saudi Electrical Company, the Ministry of Petroleum, the Electricity and Cogeneration Regulatory Authority, and many other stakeholders.
Most recently, the Center for Complex Engineering Systems (CCES) was established as a joint effort between MIT and King Abdulaziz City for Science and Technology (KACST) to study multi-domain interactions in complex systems such as water, energy and transportation. Also, the Ministry of Petroleum and Saudi Aramco have established the King Abdullah Petroleum Studies and Research Center (KAPSARC) to study solutions to the energy challenges.

With so many stakeholders and entities addressing the energy problem, one might anticipate redundant studies and initiatives that would be prolonged and costly. SEEC is working closely with all stakeholders and research centers to streamline efforts and reach the most optimal solution through the collaboration of all entities.

Study and research regarding the kingdom’s energy problem are clustered in seven focus areas:

- Deployment of solar farms across the kingdom to reduce the amount of fossil fuels required for electrical generation;
- Wind power (the kingdom is considered to have below average wind speeds for power generation but it is a viable option in some local or regional areas) (Patlitzians et al. 2006)
- Use of future nuclear energy for electrical generation;
- Energy conservation
  - Through technical efficiency
  - Through user conservation;
• Greater reliance on efficient fuels for fossil power generation;

• Replacement of legacy power generation units with more efficient and environmentally friendly units; and

• Importation of natural gas from neighboring countries to support the electrical generation demand.

This thesis investigates the combined effects of some of these energy efficiency measures on the KSA energy system, taking into account non-linearalities and coupling effects in the system.
Chapter 2: Electrical Consumption in Saudi Arabia

Current Situation

Currently fossil fuels are the sole source of electricity in Saudi Arabia. The kingdom relies exclusively on oil and gas to generate electricity and meet its demand. The types of fuel used by power generation plants are: natural gas, crude oil, diesel, and heavy fuel (HFO). The total maximum output of all types of fuel is around 40.4GW, of the four fuels used, natural gas has the highest efficiency and crude oil has the lowest as shown in Table 2.1.

<table>
<thead>
<tr>
<th>Type of Fuel</th>
<th>Maximum Output (MW)</th>
<th>Minimum Output (MW)</th>
<th>Weighted Average Efficiency</th>
<th>Average Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>19,512</td>
<td>5,441</td>
<td>30.8%</td>
<td>84.7%</td>
</tr>
<tr>
<td>Heavy Fuel (HFO)</td>
<td>10,620</td>
<td>3,416</td>
<td>33.0%</td>
<td>85.1%</td>
</tr>
<tr>
<td>Diesel</td>
<td>4,985</td>
<td>1,026</td>
<td>27.6%</td>
<td>85.1%</td>
</tr>
<tr>
<td>Arab Light Crude Oil</td>
<td>5,250</td>
<td>1,268</td>
<td>28.6%</td>
<td>83.4%</td>
</tr>
</tbody>
</table>

(MOWE 2010), (KAPSARC and LAHMEYER International 2011)

Table 2.1 – Types of Fuel Used by Saudi Electrical Company for Electrical Generation in Saudi Arabia

Oil accounts for more than 50% of fuel used for power generation. The diagram below shows the growth of fuel consumption for electrical generation, and the proportions of gas and oil used.

---

2 Weighted average according to available capacity
3 Table data shows Saudi Electrical Company only, it does not include other private companies. See Table 2.2 for full list of companies and capacities.
Figure 2.1 shows the sharp increase in fuel consumption over the past 20 years. The efficiency of thermal power plants increased from 27% in 1990 to 31% in 2009. This is mainly due to the increasing share of "gas-fired capacity", which was about 6.5% per year (Enerdata 2011). Figure 1.2 shows that fuel consumption in Saudi Arabia was ~220 TWh per year in 2009, this may seem low when compared to the total installed capacity from Table 2.2. This difference is due to seasonal demand and peak versus average power consumption, also more plants have come online since data was recorded in Figure 1.2.

The following map shows the distribution of the three types of electrical generation stations in the kingdom.
Figure 2.2 – Map of Electrical Generation Stations

Installed Capacity
The current installed capacity in the kingdom is around 55 GWh. The table below shows the number of stations in the kingdom and the capacity by generation entity. The Saudi Electricity Company (SEC) provides 74% of the total capacity; the Saline Water Conversion Corporation (SWCC) is responsible for a capacity of 5,120 MW (~10%).
<table>
<thead>
<tr>
<th>Generating Entity</th>
<th>Number of Stations</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEC</td>
<td>49</td>
<td>40,856</td>
</tr>
<tr>
<td>SWCC</td>
<td>15</td>
<td>5,120</td>
</tr>
<tr>
<td>Jubail Water &amp; Elec. Co.</td>
<td>1</td>
<td>2,942</td>
</tr>
<tr>
<td>Shauijah Water &amp; Elec. Co.</td>
<td>1</td>
<td>1,191</td>
</tr>
<tr>
<td>Tuhama Power Company</td>
<td>4</td>
<td>1,083</td>
</tr>
<tr>
<td>Marafiq (Yanbu)</td>
<td>1</td>
<td>1,038</td>
</tr>
<tr>
<td>Shaqiq Water &amp; Elec. Co.</td>
<td>1</td>
<td>1,020</td>
</tr>
<tr>
<td>Saudi Aramco</td>
<td>6</td>
<td>1,018</td>
</tr>
<tr>
<td>Rabigh Arabian Water &amp; Elec. Co.</td>
<td>1</td>
<td>481</td>
</tr>
<tr>
<td>Saudi Cement Co.</td>
<td>2</td>
<td>266</td>
</tr>
<tr>
<td>Jubail Power Co.</td>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>Total</td>
<td>82</td>
<td>55,265</td>
</tr>
</tbody>
</table>

**Table 2.2 – Electrical Generation Stations 2011**

Saudi Arabia’s Water and Electricity Ministry estimates that the country will require up to 20,000 MW of additional power-generating capacity by 2015. Current data indicate that electricity demand in the country is growing at the rate of 6% per annum (MOWE). In 2010, the increase in the generation and consumption resulted in an increase of peak load by 11.7% (reaching 45,661 megawatts) from the previous year. Actual power generation capacity grew by 5.2% (SAMA). The sharp increase in peak loads has caused troublesome power cuts. In 2006, in the central and western provinces, such occurrences resulted in major losses for industries in that region (GIH Saudi Electrical Company 2006). This is a scenario that government officials want to eliminate in the future.

**Consumption by Sector**

In 2011, total estimated electricity consumption in the kingdom was 212,262.6 GWh, which is consistent with Figure 2.1. The geographic breakdown was: 31% for the
eastern region; 30.7% for the western region; 30% for the central region; and 8.3% for the southern region (SAMA 2011). The overall increase over the previous year was 9.7%.

Consumption sectors include residential, industrial, commercial, government, and other sectors (hospitals, streets, mosques, schools). The highest consumption was in the residential sector--51.2% of the total consumption.

![Figure 2.3 – Relative Electrical Consumption by Sector (2011)](image)

**Electricity Waste Streams**

Saudi Arabia is located in a hot region with average summer temperatures of 81°-109° F in non-coastal or inland areas, and 80° -100° F in coastal areas. Air conditioning accounts for 35% of the total electrical consumption in the kingdom.

Figure 2.4 represents about 70% of the 51.2% of residential electricity consumption (ECRA 2010). At present the sun is driving major energy consumption rather than serving as a major source of energy through photovoltaics and other means such as rooftop heaters.
In addition to air conditioning, other appliances in the household use a major portion of electrical consumption. Water heating is another source. Although we were not able to find statistical data about water heaters and their consumption, electrically operated water heaters in the kingdom often run continuously in households during the short winter period.

While home appliances are necessary, the extremely wasteful Saudi consumer behavior is a significant contributor to the kingdom's energy problem. Based on personal observations as a resident and a citizen of Saudi Arabia, the author has noted several behaviors that involve needless energy use:

- Over lighting of houses, shops, and restaurants;
- Overuse of street lighting and unnecessary use of lighting on roads between towns and cities;
- Home air conditioners running at full capacity 24 hours a day, seven days a week, even while residents are not home;
• Lights kept on in unused rooms during evening hours (residential);
• Office lights kept on overnight, with little utilization of dimmer or automatic shut off functions;
• Lack of heat insulation in old buildings;
• Overuse of windows and open spaces in newer houses and buildings, which dictates air-cooling for the whole building rather than portions of it;
• Commercial shop closings between noon and late afternoon, then remaining open until late hours of the night.

The overall Saudi Arabian culture of utilizing evening hours for all kinds of activities, shopping, social gatherings, running errands, etc., drives excessive electrical consumption.

**The Price of Electricity**

The government heavily subsidizes oil and gas for electrical generation. In February 2012, the governor of the Electricity and Cogeneration Regulatory Authority (ECRA), Dr. Abdullah Alshehry, revealed that the government sells a barrel of oil to the Saudi Electricity Co. (SEC) for $2, while a barrel sold in the international market was close to $100 (Arqaam).

Commercial and private customers in the kingdom are charged $0.04/kWh of electricity, approximately 90% less than “internationally applicable market prices”. The electricity

---

4 Consumers run air conditioners with the same set-point temperatures around the clock.
5 Government subsidy is approximately equal to $2 per kWh
tariff for the commercial and private customers has been the same since 2000 (Argaam 2012), while the tariff for the industrial and government customers was adjusted in 2010. According to KAPSARC and LAHMEYER International, “Such adaptations are determined by the Ministry of Petroleum and Minerals to account for any declines in oil exports” (KAPSARC and LAHMEYER International 2011). The heavy subsidization of electricity prices is a main contributor to the consumption problem in the kingdom. Since electricity is cheap and subsidized, consumers do not feel a direct financial incentive to use electricity judiciously. It has been shown in other settings that once commodities become scarce and their true price is reflected, consumer behaviors change quickly.

However, it is part of the Saudi government’s welfare policy and culture to provide cheap and abundant electricity as a way to implicitly share the country’s oil-generated wealth with the population at large. This fundamental tension is at the root of the problem of higher than average per capita energy consumption. How can consumer behaviors be changed without radically increasing electricity prices; an action that could lead to reduced economic growth and potential civil unrest?

**Electrical Generation Efficiency**

*End user efficiency:* The government is turning some attention to reducing electrical consumption through increased efficiency for all electrical devices, from the smallest house appliances to street lighting. A great deal of savings can be realized through implementing policies on imports of electrical equipment. Through a minimal tariff on
inefficient imports, combined savings can be immense for a population of more than 27 million people. An example will be shown quantitatively in Chapter 4.

*End user efficiency*: As generation units in power plants become outdated and are due for replacement, the updates to cleaner and more efficient generators can also contribute to fuel savings.

**Summary**

In Chapter 2, we presented information about electrical generation and demand, challenges and consumption trends that contribute to the energy crisis in the kingdom. These will be used below to model the electrical consumption. Potential conservation through efficiency and user awareness is highlighted in Chapter 4. Recommendations regarding electrical consumption are made in chapter 7.
Chapter 3: Analyzing the Energy Challenge in Saudi Arabia Using System Dynamics (Building the Model)

Thesis Methodology - The System Dynamics Approach

In an attempt to analyze the energy challenge in Saudi Arabia with a focus on electrical consumption, this study investigates the issue through causal loop thinking based on a system dynamics model. A holistic view model of the electrical consumption issue will be discussed in detail in this chapter. The model will quantify the energy dynamics for the kingdom as a whole in the aggregate and will not focus on regional or local differences. A more detailed spatial analysis of energy system dynamics is left for future work.

The energy problem in Saudi Arabia did not arise only in the last few years; the government has been aware of it for several decades and has been slowly taking steps to address the issue. Many reports and analyses have been conducted and are currently being done as mentioned above. System dynamics is a powerful method that connects a matrix of variables through causal relationships (Forrester 1969; Sterman 2000). No one method can provide a comprehensive understanding of the problem, but system dynamics can provide a perspective of special use in the decision-making process.

Since Jay Forrester founded the field of system dynamics in 1957, it has been applied to an array of complex problems in business, politics, and social sciences. The field
continues to grow as the method is applied to different areas including medical, technical, and cross-domain applications.

Although system dynamics requires some assumptions, the application of sensitivity analysis and the adjustment of variables and equations can assist in building a model that reflects reality through careful calibration and can be validated through simulations and comparisons with other models and data. For the purpose of this thesis, a more holistic approach was considered, covering social, technical, political, and economic relationships to best represent the implications of different energy policies and decisions.

In this chapter, the steps in building the model are detailed along with the assumptions on constructing the feedback loops. Based on literature research, workshops, interviews with stakeholders, and collaboration with other researchers, a list of variables, stocks, and flow rates have been identified. A causal relationship diagram was then mapped based on the data gathered. The qualitative validity of the diagram was then tested and analyzed; finally, the mapped loops were labeled as either balancing (negative) or reinforcing (positive loops). At this point, the mathematical equations to complement the causal relationships were further developed in the model. Through an iterative process, the causalities and mathematical relationships were refined to prepare the model for full simulation.
Purpose of the Model
The purpose of this model is to simulate the flow of fossil (non-renewable) and alternative energy to supply electrical generation to the demand side, and to demonstrate a range of potential future impacts on GDP, energy intensity, and domestic oil consumption in Saudi Arabia during the period 2011-2046. In addition, it investigates how the system reacts to different scenarios in energy policy (alternatives, conservation). The model will provide policy makers with improved insight regarding energy policies and their impacts through the causal loop analysis. The model was built based on the most recent data available from various sources for the 2010-2011 period.

System Dynamics vs. Open-Loop Thinking

"Much of the art of system dynamics modeling is discovering and representing the feedback processes, which along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of a system." (Sterman 2000)

As highlighted in Chapter 1, many reports and analyses have been conducted regarding the energy challenge in Saudi Arabia. However, most of the work has used "open loop thinking". These generally use a linear approach – extrapolating past trends - which can be criticized for being one directional, only useful for narrow purposes, not covering side effects, and triggering policy resistance for not offering insights into intended and unintended consequences of future actions.

6 Most energy outlook reports forecast for 30 years; beyond this period, prediction becomes less accurate.
In the first chapter of *Systems Thinking and Modeling for a Complex World* (2000), John Sterman discusses the following points regarding the open-loop approach to complex analysis:

- The solutions that were implemented in the past become the problems that we are trying to solve today. “Yesterday’s solution becomes today’s problem”

- Not having full understanding and perspective of all feedbacks in a system is the main reason for policy resistance, actions taken alter the system, which creates reactions from other parties to correct the balance, then more reactions take place.

- Decisions, actions, or solutions taken within a system may eventually create a ripple effect that could result in negative and unintended consequences, hence resulting in ineffective policies.

- The interaction between “balancing” and “reinforcing” forces is what makes a system dynamic. Reinforcing loops tend to generate expansion or growth, while balancing loops are self-correcting and opposing change.

- “People generally adopt an event-based, open-loop view of causality, ignore feedback processes, fail to appreciate time delays between action and response and in the reporting of information, do not understand stocks and flows and are insensitive to nonlinearities that may alter the strength of different feedback loops as a system evolves.”
The points highlighted are the basis for a solid argument on why system dynamics is potentially an effective tool to analyze the energy challenges in Saudi Arabia. The approach can be applied to an array of complex systems concerning energy security in the kingdom.

Decision makers often assume that human behavior is purposeful, with most decisions motivated by logic based on information (Sterman 2000). If such were entirely the case it might be argued that the problem is clear and the solution is intuitive--diversifying energy sources, conservation, and efficiency policies are the answer. However, the complex energy system of the kingdom might well include “unknowable unknowns”. System dynamics is one way to test for such unknowns through feedback loop analysis.

System Dynamics Model-Building Process

The system dynamics Model-Building Process requires five steps:

1. **Problem Articulation (Boundary Mapping):** In this step, the problem statement and dynamic hypothesis are identified. The model boundaries are set, including the time horizon of the model and the variables needed based on reference modes to describe the behavior of the system.

2. **Mapping:** Causal relationships between variables, stocks, and flows are established and mapped at this stage.

3. **Formulation:** Based on the causalities of mapped variables, the nature of loops and loops' behaviors are identified, whether they are generating, reinforcing, or
balancing loops. In addition, mathematical equations are written to facilitate and instantiate the model simulation.

4. **Testing**: In this step the data introduced in the exogenous variables and stocks are initialized. The model is then checked for unit consistencies and syntax errors. A few initial simulations take place, followed by model calibration and initial validation. In this thesis the model should not only be able to predict the future behavior of the system from 2012-2040, but also replicate its past behavior.

5. **Policy Formulation and Evaluation**: Following the testing and initial simulation, the model is cross-validated with reference modes. Once the model works effectively, sensitivity analysis can be applied and different future scenarios simulated by applying different values for exogenous variables and monitoring change.

**A Systems Approach to Energy Diversification**

Literature search and extensive data analysis suggested that building a system dynamics model for the energy system in Saudi Arabia would involve a high level of complexity. Therefore, model boundaries and limitations were drawn to create a simple model that would serve the purpose of this thesis by adopting a holistic systems approach.

To begin, a clear problem was identified. This problem is embodied in the following two research questions:
1. **What are the steps that need to be taken in order to address the unsustainably increasing primary domestic energy usage in the kingdom?**

2. **How could policy actions (through conservation and/or the introduction of alternative energy) influence the domestic consumption of fossil fuels for electrical generation?**

Early attempts to simulate the current situation in the kingdom have proven to be extremely complex. The challenge of obtaining recent, accurate, and consistent data has also been difficult since most of the data resides with the individual stakeholders and the channels of communication and collaboration with the Center of Complex Engineering Systems (CCES) are still maturing. The center is presently in its first year of operation.

**Model Building**

“There is an assumption that expensive sponsorship must precede an effort to address important issues. However, if the objective is sufficiently clear, a rather powerful small model can be created, and the insights sharply focused. Often, the consequences of such a book will be so dramatic and controversial that few financial sponsors are willing to be drawn into the fray. However, the task can lie within the resources of an individual. Where are the people who can carry system dynamics to the public?”

(Forrester, 2007 p. 362)

Based on Forrester’s recommendation, the model for this study was built to capture the effect of increasing domestic electrical consumption levels on domestic oil consumption.

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7 CCES is collaboration between KACST and MIT to address an array of complex systems problems arising in the kingdom as a result of the rapid urban development and industrialization.
in Saudi Arabia, and consequently its effect on oil exports and GDP. Based on the reference modes of step one of the model-building process, model variables were identified based on model boundaries.

![Figure 3.1 - Summary of KSA Energy System Dynamics Model Boundaries](image)

Following the second step of the model building process, variable, stocks, and flows were mapped. The result was the following set of two main loops.
Explanation of the Main Causal Loops

Figure 3.2 captures the relationship between oil revenue from exports and domestic oil consumption. Domestic electrical consumption drives cumulative oil consumption in the
kingdom. Based on the explanations in Chapter 1, electrical consumption in 2011 comprised about 65% of total domestic oil consumption. The amount of domestic oil consumption subtracted from overall production levels, determines the quantity of oil that can be exported. Oil revenue from abroad is the main driver of the Saudi economy, accounting for more than 65% of the GDP. The energy consumed in the kingdom is in turn influenced by GDP. For the purposes of this model, the impact of GDP on electricity consumption levels is calculated using a regression equation based on statistical and historical data from the World Bank, the Saudi Arabian Monetary Authority, and the US Energy Information Administration. The higher the level of economic activity, the higher the GDP, the more energy will be consumed domestically.

The value of a barrel of oil equivalent (BOE) needed for electricity generation is calculated based on the amount of electrical energy, expressed in units of kWh that can be generated from a single barrel of oil:

\[ 1 \text{ Barrel of oil} = 5.8 \text{ million British thermal units (BTU)} \text{ (Investopedia; EIA).} \]

Also through regression, the amount of BOE needed for electrical generation is converted into real barrels. This amount is added to the non-electrical oil consumption before calculating the available oil export levels based on the production levels at the time. This is a “balancing” loop because the system is trying to correct and balance itself. An increase in oil export produces an increase in oil revenue, leading to an increase in GDP and then increased electrical consumption. More electricity consumed increases domestic oil consumption, thus reducing the amount of oil the system can
export assuming constant levels of production. Note that oil production levels have been near constant for the last 30 years just below 10 million barrels per day. The causal arrow between cumulative oil consumption and oil exports has a negative polarity, thus balancing the loop.

Figure 3.3 shows the reinforcing nature of introducing another source of energy to support domestic electrical consumption. This loop shares a few variables with the first loop. However, in this scenario, part of oil revenue from export is invested in alternative energy sources (such as solar, nuclear, etc.). The introduction of an alternative source of energy affects the number of real barrels of oil needed to meet domestic demand. An increase in alternative energy for electrical generation means that fewer barrels of real oil are needed because alternative energy substitutes for the burning of fossil fuels (see Table 2.1) to produce the required electricity. This loop shows a reinforcement of growth since domestic oil consumption savings enables more export and higher oil revenues, which in turn can be invested in more alternative energy or other domestic infrastructure projects, including the creation of new economic sectors that will contribute to the GDP, without depending directly on oil.

Figure 3.4 shows the combined diagram of the two interacting loops discussed above. These two interacting loops are at the core of the KSA energy dynamics. In addition, the diagram includes causal relationships to represent the effect of population growth on
non-electrical oil consumption, and the effect of oil revenue on other economic sectors, and subsequently its effect on GDP.

Figure 3.4 – Aggregate Energy Dynamics Causal Loop Diagram

Variables Used in Modeling Energy

Different variables were implemented in the system dynamics model, including exogenous variables, stocks, and flows. Figure 3.4 shows the main endogenous variables of the model, stocks and other exogenous variables were omitted from Figure 3.4 but are shown in detail in Chapter 6. Table 6.1 lists a short description for the variables used in the detailed model.

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8 This is a simplified version of the final core mode. A detailed model is discussed below; the detailed causal loop diagram is shown in Appendix A.
Main Drivers of Energy Consumption

As discussed in Chapter 1, population growth, and diversification and growth of economic sectors are the main drivers of the increased electrical consumption in Saudi Arabia. To capture these two separate yet related effects, the population effect on electrical consumption is shown in Figure 3.4 above in the lower left corner. The growth of non-oil economic sectors (including industrial expansion) also affects GDP; this growth is partially influenced by oil revenue as well as its own growth. The specific basis of the mathematical relationship is discussed in detail below.

Oil Revenue and Economic Sector Growth in Relation to GDP

In Figure 3.2, finding a mathematical equation that would best represent the relationship between Oil Revenue and GDP, and Oil Revenue and Economic Sectors and their contribution to GDP was one of the most challenging steps in building the model. This relationship can be fairly complex for a major oil- and gas- producing country like Saudi Arabia. In fact, many system dynamics models might be built to represent that relationship in detail. However, to capture the contributions of oil and non-oil economic sectors to GDP for the purposes of this model, further investigation had to be done to better understand the relationship and find simple yet adequate equations that would fit the purpose of this model.

The reliance of Saudi Arabia on oil revenue from exports as a major contributor to its GDP is not surprising, however as a result the kingdom has undergone cycles of economic booms due to high oil prices and global demand for energy. Over the past 30 years, Saudi Arabia and other Middle Eastern oil-producing countries have increased the
competitiveness of their non-oil sector in an effort to dampen the effect of down cycles of oil prices. The eventual goal is for the economic sectors that do not directly depend on oil exports to become diversified and resilient in the face of fluctuating world crude oil prices. According to Jadwa Investment, the global demand for fossil fuels as a source of energy may gradually and slightly drop as countries rely more on renewables and become more efficient (Jadwa 2011).

If we compare the labor market and the role of the states in the economy in GCC countries, including KSA, now to the situation 30 years ago, we observe a dramatic increase in economic reform programs, stability of funds, and a higher degree of economic integration within countries in the region. In fact, the financial markets in Gulf Cooperation Council (GCC) countries are now deeper and better integrated into the world system than they were in the late ‘70s and early ‘80s with the first major oil booms (Al-Moneef 2006). These factors support the growth and sustainability of the non-oil sector in oil-producing countries, both major and minor.

Dr. Majid Al-Moneef, former Governor of Saudi Arabia to OPEC explained that the contribution of the oil sector to economies takes place through five linkages:

1. **Fiscal Linkages:** Linkages relating to macroeconomic and monetary policies involve the allocation of oil revenue through government expenditure to competing needs. For example, during the period 1985-1999, some oil-producing countries initiated various measures towards economic reform. Dr. Al-Moneef explained that “on the fiscal side these measures included privatizing public
enterprises and activities, diversifying the government revenue base through fees, establishing the oil stabilization funds, adopting conservative oil price assumptions in planning government expenditures, reducing government subsidies, and reforming energy prices to reflect marginal costs."

2. **Forward Linkages:** "The actual physical output from the oil and gas sectors that feeds into the economy includes the input of oil into the refining industry, and the input of gas into feed stocks for the petrochemical industry, as well as the input of oil and gas into the electricity production", with which we are mainly concerned with in the model developed in this thesis.

3. **Backward Linkages:** This refers to the services provided to the petroleum industry by the domestic sector. Obviously such service providers would be directly affected by any decline in oil prices and demand.

4. **Consumption Linkages:** This linkage was represented in the causal loop diagram shown in Figure 3.2, regarding the impact of oil income on the country's economy. Under this linkage, a common phenomenon referred to as the "Dutch Disease" ⁹ may occur. An economy rich in natural resources and spending excessively is more susceptible to a situation in which manufactured goods become less internationally competitive and exports of manufactured goods decrease. It is common for non-oil exports to increase during periods of low oil

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⁹ The term "Dutch disease" originates from a crisis in the Netherlands in the 1960s that resulted from discoveries of vast natural gas deposits in the North Sea. The newfound wealth caused the Dutch guilder to rise, making exports of all non-oil products less competitive on the world market. ("Dutch disease" Investopedia)
prices, while imports decrease as the government spends more conservatively during the same period.

5. Socio-Political: This linkage is concerned with the impact of oil wealth on the political system and its consequent effect on the economy.

(Al-Moneef 2006)

Figure 3.5 shows the linkages between world oil price, oil revenue, GDP, and economic growth.

Figure 3.5 – The Role of Oil Revenue in GDP Evolution and Economic Growth

To best express the relationship in this part of the model, the effects of the “Dutch Disease” were considered and the following assumptions were made:

<table>
<thead>
<tr>
<th>Oil revenue contribution to GDP</th>
<th>Oil revenue contribution to the growth of economic sectors</th>
<th>Economic sectors self growth rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 25% of GDP</td>
<td>2.6%</td>
<td>2.9%</td>
</tr>
<tr>
<td>&lt; 25% of GDP</td>
<td>0%</td>
<td>3.5%</td>
</tr>
<tr>
<td>0% (no contribution)</td>
<td>0%</td>
<td>-1.1%</td>
</tr>
</tbody>
</table>

Table 3.1 - Oil Revenue Contribution to GDP Percentages

10 The model assumes that some oil revenue is a requirement for the economy to continue growing in all sectors. Although 0% revenue is not encountered during the timeline of the model, it is accounted for in the mathematical equations.
GDP in Relation to Change in Electrical Consumption Level

Diagram 3.2 shows a causal relationship between GDP and Annual Electrical Consumption. There is clearly a causal relationship between GDP and energy consumption on a national level; however, there are many arguments over the accuracy, scale, and coupling of these two variables. Some may argue that the relationship between GDP and Primary Energy Consumption maybe decoupled in response to efficiency, energy price volatility, the price of renewables, etc. However, Figures 3.6 and 3.7 show that, in fact, global GDP and total aggregate Energy Consumption are becoming tightly correlated.

Energy consumption indicators in any given country maybe altered if energy-intensive industries are offshored to other countries and the contribution of less energy intensive

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11 The percentages in this table were derived from Jadwa’s assumptions about non-oil revenue: if there is no change in tax policy and no new policies are adopted to raise non-oil revenues, we project that non-oil revenue will grow by 8% per year. This was the average annual growth rate between 2001 and 2010.)
services is increased, hence raising energy consumption in those other countries. A holistic view provides a better perspective on the relationship between energy consumption and GDP on a global scale (Tverberg 2011). The dip in the 2007-2009 period indicates that causality may exist between GDP and energy consumption as the global financial crisis and ensuing recession slowed economic activity which led to reduced energy consumption. The model developed in this thesis therefore uses GDP as a driver of electrical energy consumption.

(Tverberg 2011)

**Figure 3.7 - Energy Consumption and Real GDP for China, USA, Spain, and Japan**

The GDP to Electrical Consumption mathematical relationship of the model presented in this thesis is based on historical trends in GDP and electrical consumption for the kingdom. It could be argued that the relationship between GDP and energy
consumption in major oil- and gas-producing countries may not be as accurate or tightly linked across the time horizon due to the sensitivity of GDP to world oil prices. Many variables and dynamics affect this relationship. It is very understandable that countries with abundant energy resources like Saudi Arabia will experience a faster growth rate in energy usage than in GDP. A more interesting relationship is the change in electrical consumption and the change in GDP for Saudi Arabia.

Figure 3.8 shows the relationship between the change in electrical consumption and the change in GDP for Saudi Arabia from 1978 to 2010.

![Figure 3.8 - Saudi Arabia's Change in Electrical Consumption and Change of GDP](image)

Data source: EIA

**Figure 3.8 – Saudi Arabia’s Change in Electrical Consumption and Change of GDP**

In the period from 1980-2000, the reaction of electrical consumption to changes in GDP was delayed. However, after the year 2000, change in the two variables seems to be tightly coupled. To capture the most realistic relationship between these two variables,
the System Dynamics Model was calibrated to reflect this sensitivity in order to most accurately simulate future outcomes.

**Dynamic Complexities and Challenges to Modeling Energy Use in Saudi Arabia Using System Dynamics**

Among the many challenging elements in modeling the energy system in Saudi Arabia is an interesting factor—the non-existence of a natural supply and demand loop within the nation.

![Diagram 3.9 Natural Balancing Loops of Supply and Demand in Open Market Systems](image)

Typically, one would expect increased oil prices to reduce energy use, and vice versa. In the general case, increased supply should depress price, and increased price should increase supply.

However, while this dynamic may play out at a global scale, inside some major oil- and gas-producing countries, this common price elasticity factor does not exist. In Saudi Arabia, energy is heavily subsidized on a national scale, both for electricity as discussed earlier, and transportation gasoline which is sold at 45 cents and 60 cents per gallon, respectively for the two grades offered. This is a major challenge when comparing the energy dynamics of Saudi Arabia to that of other countries. Most previous analyses of
energy flows on a national level have been performed for countries in which price, demand, and supply variables coupled through open and transparent markets lie at the heart of their models.

For Saudi Arabia, this is not the case. In the causal loop diagram below (Figure 3.10), only the red arrows give a true representation of the status quo in the kingdom.

![Supply Demand Feedback Loop Diagram for Saudi Arabia](image)

**Figure 3.10 – Supply Demand Feedback Loop Diagram for Saudi Arabia**

For Saudi Arabia, domestic supply is driven entirely by domestic demand; it is not affected by the price, which is constant and set by the government. The Saudi Arabian Government is the sole supplier of energy; furthermore, the government subsidizes oil and gas sold to electrical generation companies. If the government were to reduce or eliminate the subsidy, thus increasing the price of oil and gas supplied, electrical generation companies would pass the price increases on to consumers, who would naturally react by reducing consumption. Such a move on the part of the government would have many implications including an increase in domestic inflation, and public
pressure on the government to lower prices or relieve living costs in some other sector (Jamshidi). One of the conclusions of this thesis is that while energy conservation and investment in alternative energy can greatly alleviate the situation, the more fundamental structural nature of the problem lies in the suppression of the natural supply-demand dynamics of electrical energy supply due to price controls and massive subsidization by the government.

The model shown in Figure 3.4 of the causal loop diagram could have easily been expanded to capture consumption by individual sectors (residential, industrial, commercial, government, and other) or regions (Eastern, Central, Western etc...). However, historical data on consumption by sector could not be obtained at the time of analysis and a sector and regional analysis is left for future work.

Another variable that could have been expanded is the type of fuel used for electrical generation, as shown in Table 2.1. The model presented here assumes that energy is either generated by gas or barrels of crude oil (based on heat content). A more accurate representation and modeling would have involved the four types of fuel used for electrical generation, each driven by demand and supply. Again, this data was not readily available historically. However, we believe that this more aggregate representation of the energy dynamics and use of oil and gas for electricity generation and other activities is sufficient at this time to gain valuable insights.
Even if data could be found, there is another challenge to accurately gauging fuel consumption by fuel type. Individual power generation stations in the kingdom may use different types of fuel based on supply and demand. For example, one of the main power plants outside of Riyadh, (the capital of Saudi Arabia), uses heavy fuel as its main source for generating electricity. However, when demand is high and heavy fuel is not available, the station resorts to burning crude oil directly to meet demand, even though this is technically less efficient. Also, Saudi Aramco (The Saudi Arabian Oil Company), the sole provider of oil and gas to the nation’s power stations, also runs its own plants, supplying power to its own facilities, offices, drilling rigs, portable houses in construction sites and plants, and residences.

The power generated by Saudi Aramco sometimes exceeds its own demand. Any excess is routed back into the Saudi electrical grid. For these reasons above, it is very difficult to map a causal loop diagram that would accurately represent the status quo at a great level of detail.

On the population side, it is a major challenge to capture the future dynamics of the model in terms of worker immigration laws, fertility, and social trends. The population is also closely tied to electrical consumption per capita, mainly at the residential level, which creates a major uncertainty in the model. Historical data shows a continuous and almost a linear increase in electrical consumption per capita (Figure 3.11). One might expect that the modest increase in oil production and the kingdom’s economy over the
past 30 years would naturally increase consumption then eventually level off or continue to increase but at a lower rate. However, the data does not show a stop in growth of electrical consumption per capita.

This variable and its hidden drivers add to the complexity of accurately modeling energy consumption in the kingdom. Other hidden technical and social factors may also affect trends. Some of the points covered in chapter 2 explain the per capita increase.

**Diagram 3.11 - Saudi Arabia’s Electrical Consumption Per Capita (kWh) Per Year**

**Summary**

In Chapter 3 we described the rationale for using system dynamics as methodology for investigating and analyzing the energy dynamics in Saudi Arabia, we then defined the purpose we seek to accomplish from the model. Detailed analysis of historical energy data were then used to derive variable relationships and describe the energy model.
building process, we presented the dynamics of the two main loops and highlighted the main drivers of energy consumption. Simulated scenarios and model output are discussed in detail in Chapter 6. In the next chapter, we discuss the topic of conservation and we present a system dynamics model to simulate a theoretical case that combines technical efficiency and consumer awareness.
Chapter 4: Electrical Conservation Through Efficiency and Awareness

This chapter presents a discussion of electrical energy conservation through two streams, technical efficiency and reduced consumption through user awareness. We then present a simple system dynamics model in an effort to understand the causalities of user conservation through awareness campaigns and technical efficiency. The motivation for this chapter is rooted both in significant literature that quantifies the value of energy conservation as well as the founding and mission of SEEC as elaborated earlier.¹²

Electrical Conservation Through Efficiency

Conservation through efficiency in Saudi Arabia is set by one main entity, the Saudi Standards Metrology and Quality Organization (SASO). The mission of SASO is "to provide consumer protection, maintain public health, safety, and environmental protection. And guarantee the well being of the general public through issuing and implementing standards, quality

¹² The model developed in this chapter is not aggregated in chapter 6 with the core model that was developed in chapter 3. It is only used to demonstrate the potential of conservation and efficiency.
and metrology systems” (Standards Metrology and Quality Organization)
(www.saso.org.sa.). Its main role is to set the standards for all manufactured and/or
imported goods in a manner that would protect the consumer.

Although SASO regulates the standards for all home appliances, the model developed in
this chapter will focus on air conditioning and the savings that can be realized. Standard
(2007/2663) mandates that the Energy Efficiency Rating (EER) for air conditioning units
may be equal to or greater than 7.5 BTU/Wh at 35 degrees Celsius, and 5.4 BTU/Wh at
46 degrees. To make the consumer aware of these standards and provide information
about any appliances and their efficiency, SASO has mandated that all devices be
labeled with the Energy Efficiency Label shown in Fig. 4.1 to provide the consumer with
full knowledge about a product’s efficiency level.

The label includes the trademark of the manufacturer and model number, cooling
capacity if it is an air conditioner, expected average electricity consumption in kWh, the
number of the SASO standard, and a star rating that reflects the efficiency level.

The Ministry of Water and Electricity and the Saudi Electrical Company (SEC) provide
consumers with a detailed guide about electrical conservation and load relief. Most
consumers (particularly residential) do not pay enough attention to the facts that such
guides provide and do not know that SEC even provides guides to help reduce
consumption. In its electrical conservation guide, SEC dedicated 98% of the text to air
conditioning and the strain it puts on electrical consumption—60-70% of a typical
building’s electric use. The guide covers all types of air conditioners and a brief
description of how an AC unit operates. It highlights the consumption of two major
parts in the AC unit, the fan and the compressor (highest consumption component).

The guide does a very thorough job of explaining consumption based on each cooling
unit’s capacity at the cooling or heating level selected by the consumer. It provides
information to enable them to reduce consumption, for example:

- Setting window AC units cooling to medium would reduce their total electrical
  consumption by 10% over a year.
- Monthly cleaning of air filters can result in 6% reduction in electrical use.
- Annual AC maintenance reduces consumption by 7%.
- The cooling capability of old AC units may drop to 50%, at which point they
  should be replaced.
- New AC units can provide 16-40% increase in efficiency.
- AC capacity should be based on room dimensions to avoid cost overhead and
  potential excessive operational cost; the guide provides recommendations.

The table below summarizes the effect of increased EER on the annual consumption of
an AC unit assumed to run for 12 hours a day.

<table>
<thead>
<tr>
<th></th>
<th>Cost of AC Unit</th>
<th>Increase in Price Per Unit</th>
<th>Annual Operation Cost</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$1582</td>
<td>-</td>
<td>$410</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>$1972</td>
<td>$390</td>
<td>$287</td>
<td>$123</td>
</tr>
</tbody>
</table>

(ESCRA Consumer Guide)

Table 4.1 – Cost of EER 7 and EER 10 AC Units
According to these figures, the pay-back period for the higher-rated unit would be around three years. A consumer could expect $123 savings in annual operating costs.

**Electrical Conservation through Awareness**

Consumer behavior, and energy consumption per capita, could possibly be the biggest factor in Saudi Arabia’s energy crisis. In the previous chapter, Figure 3.11 shows that electricity consumption per capita almost quadrupled over the past 30 years. This has not been the case for electricity alone; Figure 4.2 shows the total energy consumption per capita. We suspect that these changes are mainly driven by lifestyles and expectations for quality of life and personal comfort.

The graph shows that per capita energy consumption increased six fold during the period 1972-2008. Most of the increase occurred during the first oil boom, 1972-1983. This is mainly due to the aggressive increase in spending and infrastructure.
improvement that the government overtook during that period. Primary energy consumption then increased less aggressively as indicated on the graph.

The data shows that consumption per capita coupled with population increase must be addressed if the kingdom is to reduce consumption through efficiency. Most critically, aggressive awareness campaigns must be planned and executed carefully to educate a population used to cheap energy and wasteful behavior.

**Behavior: Areas for Reduced Electricity Consumption**

Analysis of Saudi Arab consumer behavior reveals areas in which consumption can be reduced through awareness. A central problem is that the majority of the Saudi population does not fully know nor understand either the source of electricity or the kind of subsidies the government provides to keep rates artificially low.

Low prices have spurred increased consumption. Most households tend to light their living spaces too much, both internally and externally. It is common to find the entrance, fence, garden, and other exterior surroundings of a house lit all night until the early hours of the morning when residents wake up then turn them off on their way to work or school. Household sizes vary (typical Saudi households are larger than in the U.S. and have on average 6 members per household, a number which is declining), and although lighting is safe and pleasant, it could be reduced in the late hours of the evening. In the home, people tend to turn on lights in all rooms while they are there, and in some cases most of the lights when they are not home.
As described above, another main source of electrical consumption is air conditioning. Although it is hard to tell consumers not to turn their AC units on when they are not home, selectively raising the set-point temperature is another way to reduce consumption. The consumer efficiency guide suggests AC settings and temperatures for all types of units available in the market. These settings can be changed within the human comfort zone, without greatly affecting consumer satisfaction.\textsuperscript{13}

The guide also recommends the annual inspection of AC units, air filter cleaning, and parts maintenance that all would contribute to lower consumption per unit in the long run.

Consumers might also be made more aware of electricity consumption by appliances. Personal observation indicates that the number of TVs, refrigerators, and freezers per Saudi household is among the highest in the world. Families of five or more tend to have three or four refrigerators, because a household of this size typically includes a maid and/or a driver. Saudi families of four or more cook at least two meals a day every day of the week. This means that they require extensive storage space for food.

\textsuperscript{13} Although modern AC units can cool the room in a reasonably short period, the hot summer months on the east and west coasts are coupled with high humidity. Most consumers do not want these conditions to affect their furniture and stored food, so they tend to leave AC units running at all times.
In the last 15-20 years, there has also been an evolution in the way middle class Saudis design their living spaces. As more houses in Saudi Arabia are built on the modern open-space plan, home owners are likely to build a second kitchen, which they refer to as the “dirty kitchen,” where most of the daily cooking takes place, the “dirty kitchen” is usually external to the house, or connected through a small door that prevents cooking odors from spreading to the rest of the house.

The increased use of dirty kitchens has naturally increased the number of kitchen appliances in a single household. Although not all appliances are running at the same time, standby operations and unnecessary consumption have been contributing to electrical bills. Another common practice has been the building of a small, occasionally used kitchenette on the second floor of a residence. This brief description demonstrates that architectural practices and building codes need to be an integral part of an energy efficiency strategy. Cultural trends and the desire for higher standards of living and comfort need to be taken into account as they often run counter to traditional views of how efficient energy use can be achieved.

**A Combined Approach to Conservation: Efficiency and Consumer Behavior Working Together**

In this section, a simple system dynamics model is presented to demonstrate the effect of reducing energy consumption through a combined effort, including energy efficiency and consumer behavior. In this model the number of households is included as a variable. It is estimated that there are currently four million households in Saudi Arabia,
each with an average of 6-7 members per household, with an increase of 4.48% annually in the number of households (AmelInfo 2007).

The purpose of the model is to show the effectiveness of coupling increased technical efficiency and public awareness to reduce electricity consumption in the residential sector.

**Efficiency Model Assumptions**

- Four million households
- 1.8% annual increase in households (regardless of family size, which is decreasing)\(^{14}\)
- Average family members per household: Five people\(^{15}\)
- Average number of AC units per household: Seven (a low assumption)\(^{16}\)

The model assumes that one type of AC unit is being used across the country, and that the government wants to replace all EER 7 AC units with EER 10 AC units. All new models sold in the market are assumed to be EER 10 AC units.

Data from Table 4.1 will be used.

\(^{14}\) Although data indicated a 4.8% increase in the number of households, that percentage was reported in 2007, the increase has been significantly reduced due to high real estate prices. The model assumes 1.8% increase to conform to projected population. A 4.8% would yield very high population if 5 family members per household were considered.

\(^{15}\) The average family members per household are around 6, a more conservative assumption is considered here in anticipation of reduced members per family in the future.

\(^{16}\) Although there are different types of air conditioners used in residential buildings in Saudi Arabia, this model assumes that only window AC units are used.
<table>
<thead>
<tr>
<th>EER</th>
<th>Cost of AC Unit</th>
<th>Increase in Price Per Unit</th>
<th>Annual Operation Cost</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$1582</td>
<td>-</td>
<td>$410</td>
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</tr>
<tr>
<td>10</td>
<td>$1972</td>
<td>$390</td>
<td>$287</td>
<td>$123</td>
</tr>
</tbody>
</table>

- Ten percent of current households have efficient (EER 10) AC units.
- All new houses install EER 10 AC units.
- Government will subsidize 20% of the cost of replacing an EER 7 AC unit with an EER unit. The replacement rate increases as more savings are realized and is driven by publicly publishing cost-saving reports. The more people hear about savings the more replacements take place.

**Awareness Model Assumptions**

- Saudi Arabia’s literacy rate is at 78% (IndexMundi 2012).
- 10.5% of those subjected to awareness information (printed, verbal, visual, etc) adopt better electrical consumption practices.\(^1\)
- The entire literate population is exposed to awareness advertising.
- Awareness campaigns cost $115 per person.
- The internal return rate on investment is \(\sim47\%\) ($55 in annual savings).
- The price of electricity remains constant at $0.04 / kWh.
- Current per capita consumption is 7400 kWh / year.
- The objective is to reduce consumption per capita to 5700-6150 kWh / year (the model assigns a random value within that interval).

\(^1\) This value represents the affectivity of the awareness campaign, the value assumed was based on sensitivity analysis.
• Each person comes across a conservation ad eight times every year (actual exposure is more, but the assumption is that the individual fully understands and comprehends the material eight times.)

Conservation Causal Loop Diagram

Figure 4.3 – Causal Loop Diagram of Consumer Awareness and Efficiency Conservation

In this diagram, the development and effect of consumer awareness is represented by the red arrows. The effect of efficiency increase in electrical consumption is represented by the green arrows.

In the consumer awareness section, the government invests in an aggressive awareness campaign to reduce the per capita consumption of electricity, targeted primarily at the
use and replacement of AC units. The model relies on campaign ads and the spread of practices through word of mouth and interactions between individuals who adopt conservation practices and individuals who are most likely to be influenced or educated.

In the efficiency section on the right of Fig. 4.3, the government subsidizes the cost of replacing old AC units with new more efficient AC units. New households can only install efficient AC units, since they are the only ones sold. The replacement rate increases as more people become aware of potential savings through the publication of the realized savings of the customers who replaced their old inefficient AC units. Electrical bills would include statistical information about the monthly savings that might be obtained from switching to a more efficient AC unit.

**Results of a Combined Approach**

After simulating the model based on the assumptions listed above, we observe that 2.5 million households currently running less efficient AC units would convert to EER 10 AC units by 2022 at which time an equal number of households would be equipped with old inefficient and new efficient AC units (Figure 4.4). Although the conversion process would continue, less efficient AC units currently installed in households would most likely reach their maximum lifetime, if well maintained, within 25 years.
The proposed assumption is that the government would subsidize 20% of the cost of replacement. Figure 4.5 shows the cost of replacement, and the government’s contribution through subsidy, assuming that the number of households continues to increase at the current rate, and that each household includes seven AC units.
Figure 4.6 shows that, if cash savings for each efficient AC unit are $123 per year, the cumulative savings for consumers at the year 2026 would exceed $9 billion, assuming the fixed cost of $0.04/kWh.

![Diagram showing annual savings from running efficient AC units](image)

**Figure 4.6 – Annual Savings from Running Efficient AC Units**

The awareness campaign targets reduction in the electrical consumption per capita, currently at around 7400 kWh. The target is in the range between 5700-6150 kWh / year (the model assigns a random value within that interval). If the whole targeted population (70% of the 2011 population) would adopt conservation practices by 2021, the value of annual savings would range between $0.9 and $1.2 billion. The assumption is that the influence of conservation behavior would spread within households and the rising generation would learn a new model of more conservative energy use.
The main purpose of this model is to show that significant savings can be realized through an aggressive combined approach. So far, all data indicate that actions across all domains including conservation are most critical within the next 15 years. Despite inevitable pressures (the invention of new appliances, increased modes of home entertainment, etc.) to increase per capita electricity consumption over time, the goal is to control the increase and to minimize it. The savings from the combined approach discussed above are shown in Figure 4.8. The continuous increase in the combined savings curve is based on the annual savings per AC unit coupled with an increase in the number of households. Analysis of the period 2016-2021 shows that the effect of the combined approach accelerates as conservation practices spread and savings from AC unit replacement are gradually realized.

\[ \text{Figure 4.7 – Value of Savings after Consumer Awareness has been achieved}^{18} \]

\[ \text{Value of savings : Awareness 3} \]

\[ \text{The model assigns random values for the targeted per capita consumption 5700-6150 kWh / year.} \]
Conservation Modeling Overview

While the model in this chapter is based on real data provided by MOWE and SEC, the awareness portion is highly theoretical and consumer behavior may be less predictable. A more concrete way to simulate the awareness portion of the model is to hypothesize an increase in residential electrical tariffs. In reality, such an approach might involve political implications, and increase pressure on the government to reduce the cost of living in other areas. However, as a rise in price is inevitable given the current situation, this exercise might have greater relevance. Unless major reforms take place, increased electricity rates might be the strongest and most effective method to induce conservation practices in the populace. This would introduce at least a partial dynamic where price elasticity might come to play and help balance supply and demand in a more natural way as shown in Figure 3.10.
Chapter 5: Solar Power

Among all the options for energy diversification, the kingdom will most likely base its energy production on three sources in the future: fossil, solar, and nuclear. Saudi Arabia is undertaking major deployments of solar power. In June 2011, the Saudi Petroleum Minister Ali Al-Naimi said that the kingdom’s solar energy exports will eventually equal its oil exports. Although solar energy has yet to come online at large capacity, the kingdom has already implemented it as the main source of electricity for the Farasan Islands in the Red Sea (Mahdi 2011).

Given its geographical location, sunny and warm climate, peak sunlight hours, and the available land areas on which solar farms can be built, Saudi Arabia has great potential to become heavily reliant on solar energy for electrical generation and other uses. This is extremely significant as it has the long-term potential of turning the sun from an enemy into an ally as far as the energy dynamics of the country are concerned.
Sites and Potentials

A recent study of potential solar sites was recently undertaken by LAHMEYER International in cooperation with the King Abdullah City of Petroleum Science Research Center (KAPSARC). Thirteen global horizontal irradiation (GHI) measurements were conducted in different areas of the kingdom to identify promising locations for PV solar facilities. The study showed that 2,100 kWh/m$^2$ per year is achievable in the

\[19\] GHI is the shortwave radiation received on a surface horizontal to the ground (3TIER.com)
northeastern part of the kingdom in the town of Qaisumah (location 1 on the map), and 2,450 kWh/m² per year in the city of Sharurah (location 2 on the map). As for solar thermal applications like rooftop heaters, direct normal irradiation (DNI) was measured at 1,950 kWh/m² in Jeddah in the western region (location 3 on the map) and 2,600 kWh/m² per year in the city of Tabuk in the northwestern region in the kingdom (location 4 on the map). Note that a rough validation of this data is possible by assuming that of the solar constant of 1,361 W/m² reaching the Earth in space about 47% reaches the surface, i.e. 640 W/m². With an assumed 10 hours of sunshine per day and 365 days per year one reaches an irradiation level of approximately 2,300 kWh/m² per year which is on par with the numbers shown in Figure 5.1. The world average solar irradiation is approximately 164 Watts per square meter over a 24-hour day, resulting in approximately 1,400 kWh/m² per year. Most locations in Saudi Arabia therefore exceed the potential world average for solar energy generation by about 64%. This is a major potential strategic advantage and, unlike petroleum reserves, this source of energy is inexhaustible at least on the timescales we are considering here.

What Type of Solar Technology is Most Suitable for Saudi Arabia?
Several different solar technologies are currently available. The main types that are discussed and used are photovoltaics (PV), concentrated solar power (CSP), and solar thermal energy using parabolic troughs. CSP seems to be promising, though it comes with a high cost and varying efficiencies depending on temperatures. PV has a lower

20 DNI is the solar radiation received per unit area perpendicular to the rays that come in a straight line (3TIER.com)
cost that continues to decline. PV can be either fixed or tracked using one or two axes (Bas 2010). Solar energy providers can choose among five technology options associated with thin PV or crystalline PV.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Thin-Film</th>
<th>Crystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Amorphous Silicon</td>
<td>• Mono-Crystalline</td>
</tr>
<tr>
<td></td>
<td>• Copper-Indium Diselenide (CIS)</td>
<td>• Poly-Crystalline</td>
</tr>
<tr>
<td></td>
<td>• Cadmium-Telluride (CdTe)</td>
<td></td>
</tr>
</tbody>
</table>

(KAPSARC and LAHMEYER International)

**Table 5.1 – PV and Crystalline PV Technologies**

The choice of technology depends on the location of the solar farm and irradiation level in the region. A major factor is the ratio between DNI and GHI, which differs based on location. Fixed PV is most appropriate when the DNI/GHI ratio is 0.8 and below. PV that tracks the path of the sun along the sky performs better for ratios between 0.8 and 1.2, and crystalline PV for ratios of 1.2 and higher. Saudi Arabia has an average ratio of 1.1 DNI/GHI, which makes the two axes tracked PV the technology of choice for the kingdom (KAPSARC and LAHMEYER International 2011).
Figure 5.2 – Solar Performance of Fixed PV is the integral under this curve

Figure 5.3 – Solar Performance of Tracked PV increases energy collected by 52%

The two charts above show the difference in performance of fixed PV vs. tracked PV in the same location on a given day. With fixed PV the peak power output was reached briefly around noon (11:30AM-12:30PM), while with tracked PV peak power was reached around 9:30AM and slowly dropped off in the afternoon. The peak power range lasted between 9:00AM to 2:30PM.
Cost and Efficiency of Solar Cells

Solar research and energy demand are the main drivers for the development of solar power. In the past 30 years, there have been significant improvements in the solar power industry. The chart below shows the evolution of solar technologies, efficiencies, and the entities behind this development. For example, the National Renewable Energy Laboratory (NREL) in the United States has driven important improvements in the development of three-junction concentrators and has also played a big role in the development of thin film PV. Sharp, Siemens, and Plextronics have focused on PV cells utilizing organic and dye-sensitized cells. The efficiency of the most heavily used multicrystalline silicon cells is currently around 20%. Thus, if say 600 Watts of solar power impinge on a unit area of such cells, the effective electrical power output will be around 120 Watts.
The cost of solar cells has declined significantly over the past 35 years. The chart below shows the decrease in prices over three generations of PV.

![Chart showing efficiency vs. cost for three solar cell generations](image)

**Figure 5.5 - Efficiency vs. Cost of Three Solar Cells Generations**

The first generation of solar cells (green area I) involved intensive energy and labor, which kept production cost high. Its efficiency was also limited by the use of single-junction silicon, which has a theoretical limited efficiency of 33%. The second generation (yellow area II) was based on new materials that reduced both the costs and energy required for production. The Third-generation solar cells (red area III), still in the laboratory stage, promises a significant increase in efficiency (30-60%) while maintaining low production costs (Bertoldi and Berger 2009; A. Saleeo 2007).

**Solar Capacity Expansion System Dynamics Sub-Model**

In the energy model developed in Chapter 3, the assumption was that the alternative source of energy in which the Saudi government will invest is solar power. Diagram 5.6 represents the causal loops and relationships between the variables related to solar expansion.
In this energy model, investment in solar energy is based on a dedicated percentage of oil revenue. In other words, every year a specific percentage of money obtained from the export of oil will be directly invested in solar power generation capability. The increase in solar power capacity is calculated using the following formula:

\[ \text{Solar online rate} = \left( \frac{\text{Investment in solar energy}}{\text{Cost per square foot}} \right) \times \text{Avg. output per square foot} \times \text{Avg. peak sunlight} \]

There is also a delay factor which is the time required to bring solar power generation online from the time of the original investment to the time it is connected to the grid. Since the model is simulated over a period of 30 years into the future (2010-2040), we may assume that the cost per square foot will continue to decrease while efficiency continues to increase over time as shown in Figure 5.4. The obsolescence rate or lifetime of solar panels is assumed to be 25 years. (Industry lifetime estimate for PV is typically 20-30 years.) The model uses the following industry average values:

---

The solar power causal loop diagram is incorporated into the aggregated model in Chapter 6 (Figure 6.1)
• Current PV cost per square foot: $95
• Current PV average output per square foot: 10.6 Watts/hour

The average peak of sunlight hours in the kingdom is assumed to be five hours per day, and it is assumed that it takes two years from investment to operation for a solar installation.

These realistic assumptions were used to simulate the introduction of a non-fossil power source. Once large-scale deployments take place and future solar expansions become clear in terms of scale and cost, similar causal loop diagrams can be used to accurately calculate and simulate solar expansion, based on specific technology and location choices. The model presented above does not include the cost of storage or the cost of integrating solar power to the grid; this is a potential area for future work.

Other Potential Uses for Solar Power in the Kingdom
Solar power also has potential for water desalination and small-scale residential use for rooftop water heating. As noted above, a growing source of water in the kingdom is desalination. Currently, this is associated with large oil consumption to meet increasing demand. The expansion of solar deployments could include an opportunity to dedicate part of the power produced to water desalination. According to KSA Economic Insight 2011, “Solar powered desalination will be the way of the future.”

IBM and Saudi Research Institutes are currently constructing a pilot solar-powered desalination plant. It will have a capacity of 30,000 m³/d in the first phase. The second
phase would increase the capacity 10 fold to 300,000 m³/d. The initial phase alone can meet the needs of 100,000 people (KSA Insight 2011).

Solar power will also be available on a smaller scale for residential water heating. Small scale bundled systems for residential water desalination may already be purchased in the Saudi market.
Chapter 6 Aggregate Energy Model and Simulation Results

In this chapter, the causal loop diagram of the system dynamics model that was developed in Chapter 3 is presented in detail. The solar expansion model (Figure 5.6) is also incorporated into the model. Four different scenarios are then presented and simulated, and a set of variables is monitored as the output of each simulation.\(^{22}\)

**Aggregate Model**

The diagram below is a detailed aggregate representation of the KSA energy system dynamics causal loop diagrams shown in Figures 3.2 and 3.3 in Chapter 3. The variables shown in green are the exogenous variables that are determined either by government policy or the markets. The variables shown in red are the key outputs of the model we intend to influence and monitor.

---

\(^{22}\) The Conservation Model Presented in Chapter 4 is not included in the aggregate model. The Conservation Model was presented to demonstrate the concept of combining awareness and technical efficiency to achieve significant energy conservation. Creating a similar model on a macro scale that can be aggregated at a national level is an area for future work.
Figure 6.1 - Model Structure and Feedback Loops Diagram
The following table describes the endogenous, stock, and flow variables in the model.

<table>
<thead>
<tr>
<th>Endogenous Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil export</td>
<td>The amount of oil exported from KSA</td>
</tr>
<tr>
<td>Oil revenue</td>
<td>The revenue gained from selling oil on the world market</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>Barrels needed</td>
<td>The number of barrels of oil equivalent (BOE) needed to meet the electricity demand inside the kingdom</td>
</tr>
<tr>
<td>Final amount of BOE required for electrical generation</td>
<td>The number of barrels of oil equivalent needed for electrical generation after solar energy oil-equivalents are subtracted</td>
</tr>
<tr>
<td>Aggregated domestic oil consumption</td>
<td>All oil consumption including electrical and non-electrical demand</td>
</tr>
<tr>
<td>Real cumulative domestic oil consumption</td>
<td>The actual oil consumption in barrels after converting from BOE</td>
</tr>
<tr>
<td>Energy Intensity</td>
<td>The amount of energy in BTU needed to generate a dollar of GDP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stock Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual electrical consumption level</td>
<td>The annual demand for electricity</td>
</tr>
<tr>
<td>Contribution of economic sectors</td>
<td>The level of contribution of non-oil sectors</td>
</tr>
<tr>
<td>KSA oil production</td>
<td>The annual production average representing the actual number of oil barrels produced and not the theoretical production capacity</td>
</tr>
<tr>
<td>Cumulative solar energy</td>
<td>The annual contribution of solar power to electrical generation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical demand increase/decrease</td>
<td>The rate increase/decrease in demand for electrical power generation</td>
</tr>
<tr>
<td>Solar power online rate</td>
<td>The rate at which solar power generation capacity is implemented after investment</td>
</tr>
<tr>
<td>Production increase rate</td>
<td>The rate of oil production capacity increase</td>
</tr>
</tbody>
</table>

Table 6.1 – Endogenous, Stock, and Flow Variables

**Accounting for Population in the Model**

Population is a major driver of energy consumption as discussed in Chapter 1. Figure 6.2 is the population stock flow model used to simulate the scenarios below.
The model assumes an initial population of 27,136,900 in 2011. The initial birth and death rates are anticipated to be 24 per 1000/year and 3.33 per 1000/year, respectively. Though the population has been increasing steadily over the past 40 years, the rate of growth is expected to slow down and settle at a growth rate much slower than it has been during the recent boom years. Factors depressing the future fertility rate in Saudi Arabia include the cost of living, divorce rate, and women entering the work force in greater numbers.

The model assumes a decrease in fertility in the birth rate dropping by 2.5 births per 1000/year every 12 years. It is impossible to forecast future population outlook accurately. The Population Division at the United Nations (2006) predicts the population of Saudi Arabia to be between 54-60 million by 2050. The simulation output
shown in Figure 6.3 reflects a slightly more conservative estimate of population (approximately 52 million by 2050).

![Figure 6.3 - KSA Population Prediction 2012-2082](image)

The population continues to grow but at an increasingly decreased rate. By simulating the model on a longer time range, the curve starts to reflect the reduced birth rate after 2060 until it levels off at 5 births per 1000/year.

**Four Scenarios**

Table 6.2 outlines four theoretical scenarios for the future of energy policy in Saudi Arabia. Of these, the fourth scenario is the richest in the sense that it combines multiple policy actions.
1: Base Case (BAU)

This scenario reflects business as usual (BAU) in which Saudi Arabia continues to consume energy as it does today, with no action in terms of alternative energy, efficiency, or greater reliance on natural gas for electrical generation. This is the BAU scenario but with an annual increase in the percentage of electrical demand fulfilled by natural gas (the increase takes place over a 10-year period). The source of the gas is not elaborated in detail but could come from increased domestic production or from imports.

2: Increase Natural Gas Use

This scenario builds on the second scenario of increasing natural gas used for electricity generation, by introduction of solar energy as an additional source for electrical generation. This scenario shows all the previous scenarios combined with the addition of the effect of a government efficiency policy aimed at reduction of electrical demand.

3: Solar Power

4: Efficiency Policy

Table 6.2 – Four Scenarios for Future Energy Policy in KSA

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Base Case (BAU)</td>
<td>This scenario reflects business as usual (BAU) in which Saudi Arabia continues to consume energy as it does today, with no action in terms of alternative energy, efficiency, or greater reliance on natural gas for electrical generation. This is the BAU scenario but with an annual increase in the percentage of electrical demand fulfilled by natural gas (the increase takes place over a 10-year period). The source of the gas is not elaborated in detail but could come from increased domestic production or from imports.</td>
</tr>
<tr>
<td>2: Increase Natural Gas Use</td>
<td>This scenario builds on the second scenario of increasing natural gas used for electricity generation, by introduction of solar energy as an additional source for electrical generation. This scenario shows all the previous scenarios combined with the addition of the effect of a government efficiency policy aimed at reduction of electrical demand.</td>
</tr>
<tr>
<td>3: Solar Power</td>
<td></td>
</tr>
<tr>
<td>4: Efficiency Policy</td>
<td></td>
</tr>
</tbody>
</table>

Scenario 1: Base Case Scenario

Base case variable assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>World oil price</td>
<td>$110</td>
</tr>
<tr>
<td>KSA oil production</td>
<td>10 million barrels per day</td>
</tr>
<tr>
<td>Production increase rate</td>
<td>1.8% per year, 2% when exports fall below 2.3 million bbl/day</td>
</tr>
<tr>
<td>Annual Initial electrical consumption level</td>
<td>212,263,000,000 kWh</td>
</tr>
<tr>
<td>GDP Contribution of economic sectors</td>
<td>$140 Billion</td>
</tr>
<tr>
<td>Electricity from Natural Gas</td>
<td>41% of demand (static)</td>
</tr>
</tbody>
</table>

23 GPD and contribution of economic sectors are sensitive to oil revenue contribution to GDP
The model also assumes that no actions are taken to increase oil production to meet demand beyond the values set above. No alternative energy or energy conservation policies are introduced.

Using the simulation outputs discussed below we may examine and compare different variable outputs. The intersection of two variables, daily domestic oil consumption, and daily oil exports, is used to observe model behavior in different scenarios. This is the crossover point of the red and blue lines shown in Figure 6.3.

**Scenario 1 Base Case Simulation Outputs**

![Figure 6.4 - BAU Oil Production, Local Consumption, and Export](image)

In Figure 6.4, model simulations show that the daily amount of oil exported will equal the amount of domestic oil consumption in about the year 2026. Local demand for oil would exceed production capacity around the year 2046 without expansion of capacity.
Figure 6.5 shows a rapid increase in demand for domestic KSA electricity over the next 35 years. Around the year 2028, demand is expected to double from its current levels, a major concern for government officials in the kingdom.

Model Validation
The base case (BAU) scenario model prediction concurs with two other BAU model predictions that have been published recently in terms of the intersection of export and domestic consumption of oil in KSA. The intersection occurs at the year 2026 at about 5 million barrels per day. Because the method used to generate the results shown Figure 6.4 (System Dynamics Model) is most likely different from those used to generate the BAU graphs in Figures 6.6 and 6.7 below, this similarity provides some cross-validation of our model for the baseline case. Figure 6.6 from Jadwa Investment predicts that the cross over between oil exports and domestic consumption to occur around 2026 at approximately 5 million barrels per day as shown below.
In Figure 6.7, the intersection between domestic oil consumption and oil exports occurs at year the 2026, however the intersection between total production and domestic consumption (2040) occurs at an earlier time than predicted by our model shown in Figure 6.4.
Validation of the model was made by setting the exogenous stock variables for Population, Oil Production, and World Oil Price at 1990 values. The timeline was set to 1990-2011. The model was then simulated to see if the equations would drive the endogenous variables to output data curves congruent to known 2011 values (those used to simulate the BAU scenario, above). The validation simulation resulted in the following graphs.

**Figure 6.8** –Historic (1990-2011) and Model Generated (2011-2046) Daily Local Oil Consumption and Daily Oil Export

In Figure 6.8, the model was stocks initialized at 1990 values and yearly historic values for Population, Oil Production, and World Oil price were allowed to drive the model, plotting daily local oil consumption and daily oil export curves. The outcome is represented as the blue and green curves. Similarly, the Annual Electrical Consumption Level blue curve in Figure 6.9, was plotted based on historic imported data.
The model calculated GDP based on historic data is endogenously generated (blue curve). The model calculated this GDP from 1990-2011 based on the exogenous variables that were imported to the model. Furthermore, since we have actual values of GDP for the 1990-2011 periods, we plotted the data on the graph for comparison (green curve).
Figure 6.10 also shows three curves, the actual historic values of GDP (green curve), model calculated GDP for 1990-2011 based on historic imported data (blue curve), and model projected GDP (red curve). In the three figures presented above, we can see that the curve graphed based on historic data drive the model to generate close to present values for the selected variables at the year 2011. This process validates the model equations and relationships between all variables.

Scenario 2: Increase in Natural Gas Used for Electrical Generation

Saudi Arabia is heavily expanding its master gas system. With more gas plants coming on line, further explorations in the Red Sea and recent discoveries of potential onshore gas deposits in KSA, the kingdom is expected to continue to invest in increasing its natural gas-based electrical generation. This could result in higher efficiency and reduced carbon emissions, in addition to preserving a large amount of oil for exports and petrochemicals.

For the second scenario, the same assumptions from the BAU scenario are adopted, except for an increase in the percentage of electricity generated from natural gas. The BAU model assumed a constant 41%, but this case assumes a 2% increase for 10 years from 2013-2023.
As natural gas (NGL) is used for electricity increases, the intersection between daily exports and domestic consumption of oil shifts by a few years to 2028 compared to the intersection point in the BAU scenario which is around 2026. This means that local consumption exceeds export levels two years later than it did in the first scenario. Thus, the increased use of natural gas only delays the crossover point by a few years, but does not fundamentally change the structure of the energy system in KSA.

---

25 As mentioned earlier, we chose the intersection between daily domestic oil consumption and daily oil exports as a reference point to observe model behavior in different scenarios.
The increase in the percentage of electricity produced by natural gas delays the crisis by only a few years. In fact, the difference in BOE required for electrical generation (Figure 6.12) results in greater oil exports, which increases GDP and leads to higher electrical demand as shown in Figure 6.13.
Scenario 3: Introduction of Solar Energy

For the third scenario, we introduced solar energy as an alternative source by dedicating a percentage of oil revenue to investment in solar. The following assumptions were considered in addition to the previous case assumptions.

**Solar case variable assumptions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial solar capacity in 2011</strong></td>
<td>Zero kWh</td>
</tr>
<tr>
<td><strong>Installed PV cost per square foot</strong></td>
<td>$95 (decreases over time)</td>
</tr>
<tr>
<td><strong>Average output per square foot</strong></td>
<td>10.6 Watts (increases over time)</td>
</tr>
<tr>
<td><strong>Average peak sunlight hours</strong></td>
<td>5 hours (tracked PV)</td>
</tr>
<tr>
<td><strong>Solar panel lifetime</strong></td>
<td>25 years</td>
</tr>
<tr>
<td><strong>Construction delay</strong></td>
<td>2 years</td>
</tr>
<tr>
<td><strong>Percentage of oil revenue invested in solar energy</strong></td>
<td>15% of oil revenues in the first 12 years</td>
</tr>
<tr>
<td><strong>Percentage of oil revenue from 2023 onwards</strong></td>
<td>6% of oil revenues from 2023 onwards</td>
</tr>
</tbody>
</table>

Table 6.3 – Scenario 3 Assumptions

**Scenario 3 Simulation Outputs**

![Graph showing annual electrical consumption and solar power contribution](image)

*Figure 6.14 – Scenario 3 Electrical Consumption Level and Solar Power Contribution*
In this case, aggressive investment in solar energy meets a significant proportion of demand in the first 20 years even though electrical consumption continues to grow rapidly (Figure 6.14). In addition, daily local oil consumption and daily oil export curves intersect further into the future than in the first and second scenarios. The model behaves in a fashion similar to the second case, but the crossover still occurs a few years further down the line, around 2033 (Figure 6.15).

A quick and simple conclusion based on the model's behavior in the second and third scenarios is that an introduction of any alternative source of energy provides only a temporary solution, if realistic assumptions are made about the speed and magnitude at which alternative energy can be adopted. It does, however, delay the crisis point at which the level of consumption leads to energy shortages.
Scenario 4: Government Efficiency Policy

Review of the previous three scenarios leads to the obvious conclusion that the energy crisis in Saudi Arabia cannot be resolved at this stage by diversification alone. Simply increasing and diversifying the supply side of the energy problem is insufficient to achieve fundamental structural change. To achieve a more positive outcomes and a sustainable equilibrium, the current high energy consumption levels need to be reduced. It is possible that potentially energy prices would need to be increased to pressure consumer behavior through effects of price elasticity in domestic and commercial electrical energy consumption. Other aggressive actions may be needed to significantly change domestic consumption levels.

In the fourth scenario, the assumption is that the government mandates an aggressive and well planned energy policy designed to decrease domestic consumption within two years based on the dynamics similar to the model explained in Chapter 4 but on a larger scale across all sectors. The simulations for this scenario include an increase in natural gas used for electrical generation as in scenario 2; the introduction of alternative energy in the form of solar PV as in scenario 3; and an implementation of a government efficiency policy to reduce consumption.

Efficiency Assumptions
The model assumes significant reduction in domestic electrical consumption and a 15% reduction in non-electrical oil consumption.
Figure 6.16 – Increase of Energy Consumption as a Function of GDP

A better explanation of the desired behavior is the relationship between GDP and electrical consumption for a given nation. Figure 6.16 shows two graphs, the first graph reflects a nation with abundant and cheap energy resources. The trend is an exponential curve in which an increase in GDP creates an unchecked increase in energy consumption.
The second graph shows the energy consumption trend in an energy-aware and efficient economy. As GDP increases over time, this nation invests capital in conservation and energy efficiency. To simulate the final outcome of becoming an aware and efficient economy, we will assume a behavior similar to that in the second graph of Figure 6.16 to see how it would affect Saudi Arabia's energy consumption.  

Saudi Arabia's development is currently based on energy-intensive industries, coupled with low domestic energy prices that encourage energy-intensive lifestyles as described in Chapter 4. The observed trend in most countries is to become more efficient with increased GDP (KSA Efficiency).

**Scenario 4 Simulation Outputs**

![Graph showing Daily Oil Production, Local Consumption, and Export](image)

**Figure 6.17 – Scenario 4 Oil Production, Local Consumption, and Export. And Scenario 1 Local Consumption**

26 In scenario 4, a behavior rather than a numerical value is assumed to simulate reduction of energy consumption on a macro-scale. Scenario 4 assumed efficiency across all sectors. Detailed sector-by-sector efficiency analysis would yield different results depending on the level of efficiency implemented.
Figure 6.17 shows the behavior of the three main variables examined in the previous three scenarios and also includes the daily local oil consumption curve (yellow) from Figure 6.4. It shows that a desired outcome is finally achieved through the implementation of an integrated energy policy that combines efficiency gains with more electricity generation from solar technology and natural gas as well as increased levels of oil production. Only this integrated policy is able to crossover between oil exports (blue curve) and domestic oil consumption (red curve) around 2041, as well as a gradual decrease in domestic absolute oil consumption after 2060 (see Appendix C). The simulation shows a reduced yet controlled oil export level with significantly dampened domestic oil consumption in 2012-2041. The simulation output above only covers a 35-year period. Too show the long-term effect of efficiency gains and the escape from the energy crisis scenarios that were discussed earlier see appendix D.

![Graph for Annual electric consumption level in GWh](image)

**Figure 6.18 – Annual Electrical Consumption Levels for all Scenarios**

27 Scenario 4 curve in Figure 6.18 represents the two-year delay in implementing the energy efficiency policy; hence the efficient output is represented from year 2013 onwards.
By examining the annual electrical consumption levels in the cases discussed earlier, we can observe that desired controlled growth can be achieved through consumption reduction and through energy diversification in a combined approach.

![Graph for GDP](image)

**Figure 6.19 – Gross Domestic Product of all Scenarios**

Given the different oil consumption levels, the fourth scenario with reduced consumption is eventually expected to yield a higher GDP as the grey curve of Figure 6.19 shows. This model does not account for the policy implications of efficiency costs; a more natural curve would yield slightly lower GDP in initial years due to increased spending for energy efficiency, government subsidies, investment in alternative energy, power plant upgrades, efficient water desalination, etc. required for an effective efficiency policy.
Figures 6.20 and 6.21 below compare the four scenarios in terms of oil consumption and energy intensity. Energy intensity is the amount of energy needed (expressed in BTUs) to produce a dollar of GDP.

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28 Energy Intensity Calculation = Primary Energy (BTU) / Population (People) / GDP Per Capita (Dollars)
Monte Carlo Simulation Analysis

In this part of the analysis we vary the assumptions over larger ranges and provide probabilistic ranges of outcomes.

In all previous scenarios we assumed constant values for exogenous variables, e.g. world oil price at $110. In reality, oil prices can be expected to fluctuate; other values can also vary according to the implemented policy. In this part of the chapter we will expand assumptions to vary over a range of values:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scenario</th>
<th>Distribution</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Oil Price</td>
<td>All</td>
<td>Random Normal</td>
<td>Min: $50; Max: $150; Mean: $110; Std. Dev.: $20</td>
</tr>
<tr>
<td>Increase in percentage of NGL</td>
<td>Scenarios 2, 3, and 4</td>
<td>Random Uniform</td>
<td>Min: 1%; Max: 3%</td>
</tr>
<tr>
<td>used for electrical generation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil revenue percentage invested</td>
<td>Scenarios 3 and 4</td>
<td>Random Uniform</td>
<td>Min: 10%; Max: 17%</td>
</tr>
<tr>
<td>in solar in the first 12 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil revenue percentage invested</td>
<td>Scenarios 3 and 4</td>
<td>Random Uniform</td>
<td>Min: 4%; Max: 8.5%</td>
</tr>
<tr>
<td>in solar after 12 years</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4 – Sensitivity Ranges of Selected Exogenous Variables

The following table expands the assumptions from Table 3.1 regarding the contribution of different economic sectors to the GDP.
Table 6.5 – Sensitivity Ranges of Growth Rates of Economic Sectors and GDP

We selected the following runs to examine the output of running a Monte Carlo simulation on the values above.

Figure 6.22 – Scenario 1 Annual Electrical Consumption Sensitivity Bounds

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29 Y-axis scale in 1000 GWh
The sensitivity analysis results presented above show confidence bounds of 50% (yellow), 75% (green), 95% (blue), and 100% (grey) for the Annual Electrical

\[ 30 \] Y-axis scale in 1000 GWh
Consumption 31. We notice that for the BAU scenario 1 (Figure 6.22) the sensitivity bound varies over a wide range throughout the timeline of the analysis, ending at year 2046 with possible ranges between ~525,000 GWh and 710,000 GWh.

In the sensitivity output of scenario 3 with solar and increased natural gas contributions to electrical generation (Figure 6.23), we observe more controlled consumption level bounds in the first 15 year. These bounds diverge in later years to cover a range that expands over time.

With the implementation of an energy efficiency policy in scenario 4, the sensitivity output in Figure 6.24 shows uniform and closely bounded confidence range of Annual Electrical Consumption Levels throughout the simulation timeline, following the two-year implementation delay period (2011-2013).

Moreover, by examining GDP sensitivities for scenario 1 (BAU) and scenario 2, we observe that although increased GDP is expected in scenario 2, the confidence range lies within a wider range of possible values (Figure 6.26) compared to the band of possible values for GDP in the BAU case which is closely bounded at end the simulation (Figure 6.25). The reason for the wider range in the second scenario is due to increased oil export. As more electrical demand is fulfilled by natural gas, the increased oil export

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31 The areas within the two outer edges of any colored area represent the boundaries of the confidence percentage it refers to. The bands are to be imagined layered on top of each other. For example, Figure 6.23 shows a 95% confidence for values between 749,000 GWh and 1,875,000 GWh. The red line represents the mean value.
translates to higher oil revenue, and higher GDP. Therefore, the effect of sensitivity ranges in Table 6.5 has a greater influence on the simulation output in Figure 6.26 resulting in GDP values being distributed over a large range throughout the simulation.

See Appendix E for more sensitivity simulation output.
Chapter 7: Conclusions and Recommendations

The model presented in this thesis is a first-step, aggregate approach to apply system dynamics analysis to a dilemma that has proved intractable through other methods. The goal is to produce a model that will aid decision makers and other researchers to better understand the implications of focusing on one aspect of the problem rather than analyzing the implications of policies through feedback loop analysis.

The World Bank Approach

Saudi Arabian government officials intend to reach energy equilibrium through higher levels of efficiency and diversification. As envisioned by the World Bank, this achievement depends on a convergence of interests: economic growth, environmental sustainability, poverty reduction, and energy security (World Bank 2006).

Figure 7.1 – World Bank’s Rationale for Energy Efficiency

The discussion in this study models specifically the aspects of energy security and energy efficiency and its coupling with economic growth. The linkages with
environmental sustainability and poverty reduction are also important and should be explored in future research.

Impacts on economic growth could be further refined by identification of many more variables and feedback loops. Increasing the level of competitiveness within the non-oil sector would pave the way toward sustainable economic growth less influenced by revenue from oil and gas. As alternatives come on line, industries will grow, and more oil and gas will be channeled to petrochemical industries. However, increased competitiveness could translate into lower wages, threatening government's poverty reduction efforts.

What may seem as a complex problem could be easily dissected using a feedback loop analysis and system dynamics. This is an area in which a modular approach to complex system dynamics models can be achieved by understanding the variables that influence each area of Figure 7.1.

**Policy Implications**

*Only a combination of interdependent policies will provide a solid base for tackling the problem and thus avoiding an energy crisis. This requires collaboration among all stakeholders.*

Analysis of the system dynamics model outputs presented in this study has immediate implications for policy makers. Perhaps most importantly, examination of domestic oil consumption in all scenarios in Figure 6.21, and the outcome of scenario 4 on the variables presented in Chapter 6 shows that there is no single way to resolve the energy challenge in Saudi Arabia. Scenarios 1, 2, and 3 revealed high domestic oil consumption that would range between 4.5 billion bbl/year and 6 billion bbl/year by 2046.
Energy price controls and subsidies should be judiciously adjusted to stimulate conservation.

As mentioned in Chapter 3 a fundamental structural element of the problem lies in the suppression of natural supply-demand dynamics of electrical energy supply by price control ($0.04/kWh) and massive subsidization by the government. This includes oil sold for both electrical generation and also for transportation.

Increasing primary energy consumption in the kingdom can be controlled and slowed by increasing the price of domestic energy across all sectors. This can be achieved while minimally affecting the welfare of citizens while slowly changing consumer behavior. Supporting measures such as subsidies for financially vulnerable people, vouchers for energy efficient appliances etc. need to accompany price increases beyond the current $0.04/kWh level. Another option would be to introduce hourly rates to reduce peak demand during the hottest days.

Since the government is committed to providing consumers with cheap energy at the current prices, an interesting method could be implemented to influence consumer behavior in terms of electrical consumption. The government can continue to provide consumers with low electricity prices at $0.04/kWh. However, the price of electricity should be raised to near world average prices, and in return, consumers are to be provided with a monthly check that compensates for the increase in electricity prices. This way the consumers still receives the same cheap energy, though it is up to the consumers to use the cash to pay for the electricity bill, or reduce their own electrical consumption and utilize the money elsewhere. Despite the difficulties in implementing this, it could result in significant savings with minimal overhead cost.
Industrial expansion must be carefully planned and balanced to avoid rapid energy demand increases that cannot be met.\textsuperscript{32}

Jadwa Investment projects an 8\% increase in the non-oil sector per year. Our model used more conservative values, 3-5\% growth for the 35-year period of the model as shown in Table 3.1. Despite the conservative assumptions in non-oil sector growth, the energy crisis still occurs in the near future as shown by scenarios 1, 2, and 3 simulations shown in Figures 6.4, 6.11, and 6.15 respectively.

Energy diversification is key to achieving energy security; the sooner the kingdom starts introducing multiple energy sources the better.

In the model, Figure 6.5 shows a rapid increase in electrical consumption levels. However, fulfilling the current demand levels by diversification would mean that less investment is required in alternatives. Addressing current demand levels (~212,000 GWh) through diversification is more economic and technically achievable than diversification to meet the demand in 2031 when demand levels double.

Early implementation will compensate for learning process delays, transmission challenges\textsuperscript{33}, and the development of best practices. Figure 6.20 shows the cost of converting energy to a dollar of GDP (Energy Intensity). The energy intensity continues to increase over time in the BAU scenario, however, resorting to natural gas and solar in scenarios 2 and 3 results in lower energy intensity levels and a slower increase over time.

\textsuperscript{32} Petrochemicals would fall under non-oil sector

\textsuperscript{33} There are some papers and discussions on the electrical transmission challenges in countries investing in renewables. In some countries electrical grids are outdated and the cost of upgrade outweighs the benefit of investing in alternatives or choosing a specific location/region for alternative energy use.
**Energy efficiency is the first and most important step in addressing the energy challenge in Saudi Arabia.**

It is easier to invest in efficiency now while oil prices are high and capital from surpluses is available. The fourth scenario simulation outputs were clear indicators of the positive effect of efficiency on the set of chosen variable indicators.

**Investing in natural gas as a temporary relief to the energy challenge maybe a good step to buy time for alternative sustainable energy development.**

To produce 1 kWh of energy, gas is $\frac{1}{3}$ the price of nuclear, and $\frac{1}{5}$ the price of solar (Jadwa 2011). An increase in natural gas utilization in scenario 2, yields outputs in Figures 6.12 and 6.13 that show potential savings in oil that otherwise would have been consumed for electrical generation, and the resulting increase in GDP. Utilizing the GDP increase, with controlled industrial expansion to lower electrical demand, would be a good step towards the development of an effective energy policy. Gas development is already underway with the expansion of the Master Gas System in the kingdom. However, gas is not renewable. Other sources should be developed to provide an energy balance that slows down the depletion of oil and gas.

Setting aside any political barriers, importing natural gas from Qatar is a technically and economically efficient and feasible solution. Both nations can benefit from the close proximity of Qatar to the Master Gas System in the eastern province of Saudi Arabia. The comparative difficulty and costs of exporting natural gas overseas should spur Qatar’s interest in channeling its gas production to the kingdom. Although this solution has not been considered or researched by anyone as yet, it may be the most economical and viable solution for the next 15-20 years. It does however create mutual dependencies between both countries that would require a closer collaboration than is currently the case.
Conservation and efficiency are key to reducing demand uncertainty

Uncertainty in energy consumption levels can be significantly reduced, by implementing a policy similar to scenario 4. Figure 6.24 is a good example, the sensitivity bounds for the Annual Electrical Consumption Levels lie between 180,000 GWh and 310,000 GWh in the first two years (delay period for implementing efficiency policy). But for the period after 2013, the sensitivity bounds are much closer indicating less uncertainty about demand needs. This allows for better and more efficient planning of the kingdom's energy strategy to reach an annual electrical consumption between 185,000 GWh and 205,000 GWh by 2014.

Future Work

Research for this study suggested some future project topics in the areas of solar power development for Saudi Arabia and other regional development studies in non-major or non-oil producing Arab countries. The model developed here also suggests that many factors could be identified to provide a more fine-grained picture of the kingdom's energy future.

Solar Research

The development of solar power includes three interesting areas of research. The first is solar deployment in the Arabian Peninsula. Many papers and consultants have provided input on this subject. The envisioned scale of deployment, the solar potential, and the statement by the Saudi Oil Minister regarding exporting solar energy are interesting topics pertaining to large-scale deployment.

In addition, the challenges of deploying solar in an environment as harsh and hot as the climate of the kingdom may present unknown obstacles and require further developments in solar technology. For example, the movement of sand and the frequent occurrence of sand storms across the Arabian Peninsula may result in lower solar absorbance by blocking sunrays. Another challenge is the high humidity coupled
with hot temperatures in the months of July and August in the coastal areas close to the Persian Gulf and Red Sea.

A second area is the potential for manufacturing solar panels and the development of solar technology in the kingdom itself. King Abdullah University of Science and Technology (KAUST) is a major stakeholder, pursuing advanced research in this area. It would be interesting to model the economic potential of manufacturing solar technologies in the kingdom and its effects on the economy through diversifying exports, providing jobs for a young and rising population, and decreasing or sustaining low energy prices for the kingdom in the future.

A third research area related to solar and alternative energy is grid storage and lower tariffs during peak hours to reduce intermittency. Solar energy cannot represent a high percentage of electrical capacity unless there is some sort of power storage. Grid upgrades including significant storage would present an interesting topic. There is no doubt that solar power can theoretically meet the totality of Saudi Arabia electrical demand or that Saudi Arabia could eventually become a major exporter of solar energy. However, because demand is present around the clock, dealing with intermittency may be the biggest challenge when deploying solar power in the kingdom.

**Regional Development**

Other possible research topics fall under the regional development of non-major or non-oil producing Arab countries. Oil has had a larger footprint than that of the oil-producing countries alone; investments in different sectors, such as tourism, in other Arab countries in the region have shaped their economies for years. It would be interesting to investigate the ways in which the energy crisis and policies taken to reduce intense energy consumption in major oil-producing countries influence other countries in the GCC and wider MENA region.
As discussed earlier, unintended consequences may arise. Any such effect could divert policymakers toward resolving a different problem, leading to a chain of unintended consequences. As George Box has sagely affirmed, “Essentially, all models are wrong, but some are useful” (1987). The application of systems analysis to the problems presented by energy consumption patterns in Saudi Arabia should be of considerable use, even if the model is wrong, by teasing out the factors included in this complex system.

**Systems Analysis**

This model developed here could be applied to specific sectors\(^\text{32}\), or to different regions in the kingdom. For example, planned capital investment in energy conservation and efficiency is an area that can be studied across different sectors, detailed future research in this area would be very valuable and would allow for more accurate modeling of energy consumption trends. Many variables and dynamics would need to be analyzed and broken down to make an accurate assumption about energy efficiency and the costs associated with it.

\(^{32}\) Residential, government, commercial, industrial, and other
Appendices

Appendix A: System Dynamics Model Diagram
Appendix B: Model Documentation and Equations

(01) "Annual elec. cons. level in GWh" = "Annual elec. cons. level"/1e+06
Units: GWh
Demand in GWh

(02) "Annual elec. cons. level" = INTEG ("Elec. demand increase" - "Decrease in elec. demand", 2.1263e+11)
Units: kWh
Total electricity production levels (including waste, non sold electricity)

(03) Annual percentage increase = IF THEN ELSE((Daily Production-Daily local oil consumption)<2.3e+06, 0.02, 0.014)
Units: Dmnl
The rate at which the production capacity increases every year
(0.014) Jadwa This variable is set to increase to 2% annual increase if Daily Export of Oil goes below 2.3 million gallons per day

(04) "Avg. output per sqr ft" = INTEG (increase in efficiency, 10.6/1000)
Units: kWh/hour

(05) "Avg. peak sunlight hrs" = 5
Units: hour

(06) "Barrels Needed (boe)" = (("Annual elec. cons. level"*(1-"Percentage of elect. from natural gas"))/kWh per oil barrel)
Units: Boe
The number of oil barrels required to fulfill the current consumption levels

(07) Births = Fertility Level*(KSA Population/1000)
Units: Births
19.34 births/1,000 population

(08) Construction delay = DELAY FIXED( 1 , 2 , 0 )
Units: Year
Time required for adding solar power capacity
(09) Contribution of economic sectors level = INTEG (Economic growth, 140)
Units: Billion Dollars
non oil revenue contribution to GDP

(10) Cost of production = KSA oil prod * 2
Units: Dollars
Cost of producing a barrel of oil

(11) Cost per sqr ft = INTEG (-decrease in cost per sqr ft, 95)
Units: Dollars
drop in solar price based on the solar price learning curve

(12) Cubic feet of natural gas needed =
("Annual elec. cons. level"*("Percentage of elect. from natural gas")) / kWh per cubic feet of natural gas
Units: Thousand Cubic Feet
The amount of NGL in cubic feet needed to fulfill a percentage of electrical demand

(13) Cumulative domestic oil consumption = IF THEN ELSE("Final amount of BOE required for elec. prod">0 ,
((3e+08*EXP(1e-08*"Final amount of BOE required for elec. prod") + Other domestic oil consumption)), Other domestic oil consumption )
Units: Boe
Aggregate domestic oil consumption in BOE

(14) Cumulative solar energy = INTEG (Solar power online rate - Solar panel obsolescence rate, 0)
Units: kWh
The total solar contribution

(15) Daily Export = Oil export / 365
Units: Barrel
The number of barrels of oil exported every day

(16) Daily local oil consumption = Real Cumulative domest oil consumption / 365
Units: Barrel
The number of barrels of oil domestically consumed every day

(17) Daily Production = KSA oil prod / 365
Units: Barrel
The number of barrels of oil produced every day
(18) Death Rate = 3.33  
Units: Deaths/People  
Deaths per 1000 people per year

(19) Deaths = Death Rate * (KSA Population/1000)  
Units: Deaths  
3.33 deaths/1,000 population

(20) decrease in cost per sqr ft = 0.04 * Cost per sqr ft  
Units: Dollars/Year

(21) "Decrease in elec. demand" = IF THEN ELSE ( "Annual elec. cons. level" - (IF THEN ELSE ( "Gov. efficiency policy" = 1 , ((3e+10)*KSA primary energy consumption) - 4e+10 , (((3e+10)*KSA primary energy consumption) - 4e+10)*0.85 ) + IF THEN ELSE ( "Gov. efficiency policy" = 1 , 4e+10*EXP(GDP*0.0041) , 1e+11*LN(GDP)-4e+11 ))/2))/0 , (IF THEN ELSE ( "Annual elec. cons. level" - (IF THEN ELSE ( "Gov. efficiency policy" = 1 , ((3e+10)*KSA primary energy consumption) - 4e+10 , (((3e+10)*KSA primary energy consumption) - 4e+10)*0.85 ) + IF THEN ELSE ( "Gov. efficiency policy" = 1 , 4e+10*EXP(GDP*0.0041) , 1e+11*LN(GDP)-4e+11 ))/2))/0 , 0 )  
Units: kWh/Year  
decrease in electrical demand

(22) decrease in fertility = IF THEN ELSE ( Fertility Level > 5 , 2.5/Delay , 0 )  
Units: Births/People/Year

(23) Delay = 12  
Units: Years

(24) Economic growth = IF THEN ELSE ( Oil Revenue = 0 , Contribution of economic sectors level*0.011,(IF THEN ELSE ( ((Oil Revenue/1e+09)/GDP) < 0.25 , (Contribution of economic sectors level*0.045) , ((Contribution of economic sectors level*0.035)+((Oil Revenue/1e+09)*0.034)) )))  
Units: Billion Dollars/Year

(25) "Elec. demand increase" = IF THEN ELSE ( ((((IF THEN ELSE ( "Gov. efficiency policy" = 1 , ((3e+10)*KSA primary energy consumption) - 4e+10 , (((3e+10)*KSA primary energy consumption) - 4e+10)*0.85 ) + IF THEN ELSE ( "Gov. efficiency policy" = 1 , 4e+10*EXP(GDP*0.0041) , 1e+11*LN(GDP)-4e+11 ))/2)-"Annual elec. cons. level")>0 , ((((IF THEN ELSE ( "Gov. efficiency policy" = 1 , ((3e+10)*KSA primary energy consumption) - 4e+10 , (((3e+10)*KSA primary energy consumption) - 4e+10)*0.85 ) + IF THEN ELSE ( "Gov. efficiency policy" = 1 , 4e+10*EXP(GDP*0.0041) , 1e+11*LN(GDP)-4e+11 ))/2)-"Annual elec. cons. level") , 0 )  
Units: kWh/Year

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Increase in electrical demand

(26) Energy intensity = (KSA primary energy consumption*10^15)/KSA Population/GDP per capita
Units: Btu/Dollar
The number of BTUs needed to generate a dollar of GDP

(27) Energy intensity kJ = Energy intensity*1.05506
Units: kJ

(28) Fertility Level = INTEG (increase in fertility-decrease in fertility, 24)
Units: Births/People

(29) "Final amount of BOE required for elec. prod" = IF THEN ELSE( (("Barrels Needed (boe)"-Number of BOE replaced)>0) , (("Barrels Needed (boe)"-Number of BOE replaced)) , 0 )
Units: Boe

(30) FINAL TIME = 2041
Units: Year
The final time for the simulation.

(31) GDP = (Oil Revenue/10^9)+Contribution of economic sectors level-(Cost of production/10^9)
Units: Billion Dollars
Saudi Arabia's Gross Domestic Product

(32) GDP per capita = GDP/KSA Population
Units: Dollars/People
Gross domestic product per capita per year

(33) "Gov. efficiency policy" = DELAY FIXED( 2 , 3 , 1 )
Units: Dmnl
For no efficiency policy use: 1; for efficiency policy use: DELAY FIXED( 2 , 3 , 1 ) DELAY FIXED( 2 , 5 , 1 ) - for efficiency with 3 year delay

(34) increase in efficiency = 0.005*"Avg. output per sqr ft"
Units: kWh/hour/Year

(35) increase in fertility = 0
Units: Births/People/Year
(36) INITIAL TIME = 2011
Units: Year
The initial time for the simulation.

(37) Investment in solar energy sources = Oil Revenue * Percentage of revenue invested in alternatives
Units: Dollars
Gov. dedicated investment in solar power

(38) KSA oil prod = INTEG("Prod. increase rate",1e+07*365)
Units: Barrel
Production Capacity

(39) KSA Population = INTEG(Births-Deaths,2.7e+07)
Units: People

(40) KSA primary energy consumption =
    (139713*(KSA Population^1.4417))/1e+15
Units: Quadrillion Btu
Total national energy consumption in BTU

(41) kWh per cubic feet of natural gas = 301
Units: kWh
One thousand cubic feet of gas (Mcf) -> 1.027 million BTU =
    1.083 billion J = 301 kWh

(42) kWh per oil barrel = 1700
Units: kWh/Barrel
The average of kWh generated from one barrel of oil (Barrel of Oil Equivalent) 1,700 kilowatt hours (kWh)

(43) Number of BOE replaced = IF THEN ELSE( Cumulative solar energy > 0 , Cumulative solar energy/kWh per oil barrel , 0 )
Units: Boe
BOE replaced by solar power

(44) Oil export = IF THEN ELSE( ((KSA oil prod)-Real Cumulative domest oil consumption)>0 , ((KSA oil prod)-Real Cumulative domest oil consumption)) , 0 )
Units: Barrel
Annual oil exports

(45) Oil Revenue = (Oil export * World Oil Price)
Units: Dollars
Other domestic oil consumption = IF THEN ELSE("Gov. efficiency policy"=1 , (3e-06*(KSA Population^2)+4.5202*KSA Population-2e+09) , ((3e-06*(KSA Population^2)+4.5202*KSA Population-2e+09)*0.85) )
Units: Barrel
Transportation and other oil consumption

"Percentage of elect. from natural gas"= 0.41+(RAMP( 0.02 , 2013 , 2023 ))
Units: Dollar
41% for scenario one
for all other scenarios use: +(RAMP( 0.02 , 2013 , 2023 ))

Percentage of revenue invested in alternatives=
PULSE( 2011 , 12 )*0.15 + PULSE( 2023 , 30 )*0.06
Units: Dollar
15% for the first 12 years and 6% for the years after

"Prod. increase rate"=
KSA oil prod*Annual percentage increase
Units: Barrel/Year
The annual increase rate in production capacity

Real Cumulative domest oil consumption=
0.7166*Cumulative domestic oil consumption+4e+07
Units: Barrels
Aggregate Domestic Oil Consumption

SAVEPER = TIME STEP
Units: Year [0,?]  
The frequency with which output is stored.

Solar panel lifetime= 25
Units: Year
The suggested lifetime of each solar panel before it’s replaced (20-30 years)

Solar panel obsolescence rate= IF THEN ELSE( Cumulative solar energy>0 , STEP( (Cumulative solar energy/Solar panel lifetime) , 2026 ) , 0 )
Units: kWh/Year
The rate at which solar panels are removed from solar farms

Solar power online rate=IF THEN ELSE( Investment in solar energy sources>0 , ((Investment in solar energy sources/Cost per sqr ft)*("Avg. output per sqr ft"*"Avg. peak sunlight hrs"*365))*Construction delay , 0 )+Solar panel obsolescence rate
Units: kWh/Year
(55) TIME STEP = 1  
Units: Year [0,?]  
The time step for the simulation.

(56) World Oil Price= 110  
Units: Dollars/Barrel
Appendix C: Scenario 4 Long Period Simulation

Scenario 4 Oil Production, Local Consumption, and Export (2011-2091)

Appendix D: Additional Monte Carlo Simulation Outputs

Scenario 1 Daily Local Oil Consumption
Scenario 1 Annual Electrical Consumption in 1000 GWh

Scenario 2 Percentage of Electricity from Natural Gas
Scenario 2 Daily Local Oil Consumption

Scenario 2 Annual Electrical Consumption in 1000 GWh
Scenario 3 Cumulative Solar Energy

Scenario 3 Daily Local Oil Consumption
Scenario 4 Daily Local Oil Consumption

Scenario 4 Contribution of Economic Sectors Level
References

A. Saleeo, L. G. (2007). Nanostructured ZnO as a solution-processable transparent electrode material for low-cost photovoltaics Stanford University.


Dutch disease http://www.investopedia.com/terms/d/dutchdisease.asp#ixzz1p2xXJFWi


Forrester, Saeed & Sterman. *Policy resistance, its causes, and the role of system dynamics in better avoiding it.*
http://www.stewardshipmodeling.com/policy_resistance.htm


Jamshidi, M. M.
*An analysis of residential energy intensity in Iran,*  
*A system dynamics approach*


Marañón-Abreu (2011), R. THE DYNAMICS OF CIRCULAR MIGRATION IN SOUTHERN EUROPE.


Narayan, P. K., & Popp, S. The energy consumption-real GDP nexus revisited: Empirical evidence from 93 countries. *Economic Modeling*


